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Appendix D
Forests

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THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES:

APPENDIX D - FORESTS

Editors: Joel B. Smith and Dennis A. Tirpak

OFFICE OF POLICY, PLANNING AND EVALUATION
U.S. ENVIRONMENTAL PROTECTION AGENCY
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MAY 1989

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PREFACE

The ecological and economic implications of the greenhouse effect have been the subject of discussion within the scientific community for the past three decades. In recent years, members of Congress have held hearings on the greenhouse effect and have begun to examine its implications for public policy. This interest was accentuated during a series of hearings held in June 1986 by the Subcommittee on Pollution of the Senate Environment and Public Works Committee. Following the hearings, committee members sent a formal request to the EPA Administrator, asking the Agency to undertake two studies on climate change due to the greenhouse effect.

> One of the studies we are requesting should examine the potential health and environmental effects of climate change. This study should include, but not be limited to, the potential impacts on agriculture, forests, wetlands, human health, rivers, lakes, and estuaries, as well as other ecosystems and societal impacts. This study should be designed to include original analyses, to identify and fill in where important research gaps exist, and to solicit the opinions of knowledgeable people throughout the country through a process of public hearings and meetings.

To meet this request, EPA produced the report entitled *The Potential Effects of Global Climate Change on the United States*. For that report, EPA commissioned fifty-five studies by academic and government scientists on the potential effects of global climate change. Each study was reviewed by at least two peer reviewers. The Effects Report summarizes the results of all of those studies. The complete results of each study are contained in Appendices A through J.

Appendix	**Subject**
A	Water Resources
B	Sea Level Rise
C	Agriculture
D	Forests
E	Aquatic Resources
F	Air Quality
G	Health
H	Infrastructure
I	Variability
J	Policy

GOAL

The goal of the Effects Report was to try to give a sense of the possible direction of changes from a global warming as well as a sense of the magnitude. Specifically, we examined the following issues:

- sensitivities of systems to changes in climate (since we cannot predict regional climate change, we can only identify sensitivities to changes in climate factors)
- the range of effects under different warming scenarios
- regional differences among effects
- interactions among effects on a regional level

- national effects
- uncertainties
- policy implications
- research needs

The four regions chosen for the studies were California, the Great Lakes, the Southeast, and the Great Plains. Many studies focused on impacts in a single region, while others examined potential impacts on a national scale.

SCENARIOS USED FOR THE EFFECTS REPORT STUDIES

The Effects Report studies used several scenarios to examine the sensitivities of various systems to changes in climate. The scenarios used are plausible sets of circumstances although none of them should be considered to be predictions of regional climate change. The most common scenario used was the doubled CO_2 scenario ($2XCO_2$), which examined the effects of climate under a doubling of atmospheric carbon dioxide concentrations. This doubling is estimated to raise average global temperatures by 1.5 to 4.5°C by the latter half of the 21st century. Transient scenarios, which estimate how climate may change over time in response to a steady increase in greenhouse gases, were also used. In addition, analog scenarios of past warm periods, such as the 1930s, were used.

The scenarios combined average monthly climate change estimates for regional grid boxes from General Circulation Models (GCMs) with 1951-80 climate observations from sites in the respective grid boxes. GCMs are dynamic models that simulate the physical processes of the atmosphere and oceans to estimate global climate under different conditions, such as increasing concentrations of greenhouse gases (e.g., $2XCO_2$).

The scenarios and GCMs used in the studies have certain limitations. The scenarios used for the studies assume that temporal and spatial variability do not change from current conditions. The first of two major limitations related to the GCMs is their low spatial resolution. GCMs use rather large grid boxes where climate is averaged for the whole grid box, while in fact climate may be quite variable within a grid box. The second limitation is the simplified way that GCMs treat physical factors such as clouds, oceans, albedo, and land surface hydrology. Because of these limitations, GCMs often disagree with each other on estimates of regional climate change (as well as the magnitude of global changes) and should not be considered to be predictions.

To obtain a range of scenarios, EPA asked the researchers to use output from the following GCMs:

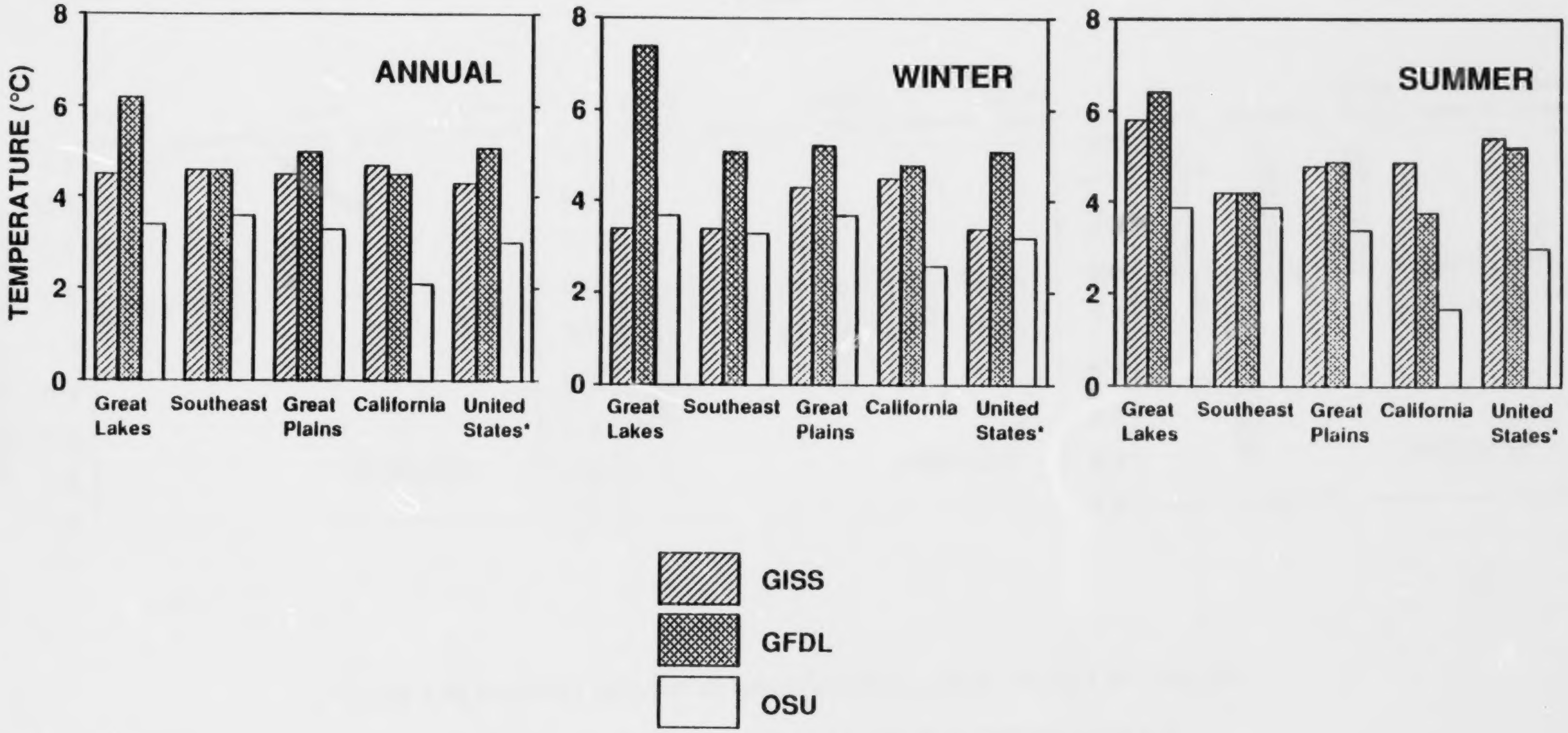
- Goddard Institute for Space Studies (GISS)
- Geophysical Fluid Dynamics Laboratory (GFDL)
- Oregon State University (OSU)

Figure 1 shows the temperature change from current climate to a climate with a doubling of CO_2 levels, as modeled by the three GCMs. The figure includes the GCM estimates for the four regions. Precipitation changes are shown in Figure 2. Note the disagreement in the GCM estimates concerning the direction of change of regional and seasonal precipitation and the agreement concerning increasing temperatures.

Two transient scenarios from the GISS model were also used, and the average decadal temperature changes are shown in Figure 3.

FIGURE 1. TEMPERATURE SCENARIOS

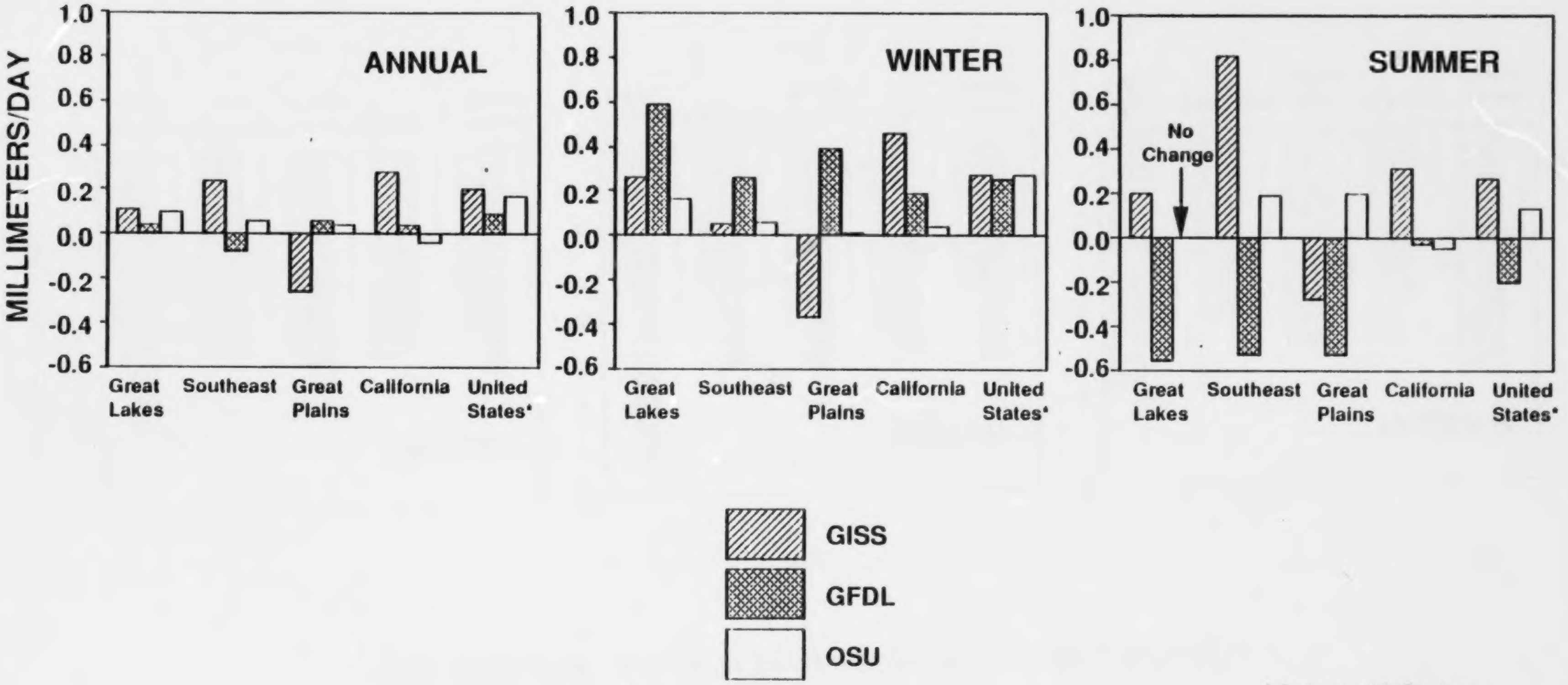
GCM Estimated Change in Temperature from $1xCO_2$ to $2xCO_2$



* Lower 48 States

FIGURE 2. PRECIPITATION SCENARIOS

GCM Estimated Change in Precipitation from $1xCO_2$ to $2xCO_2$



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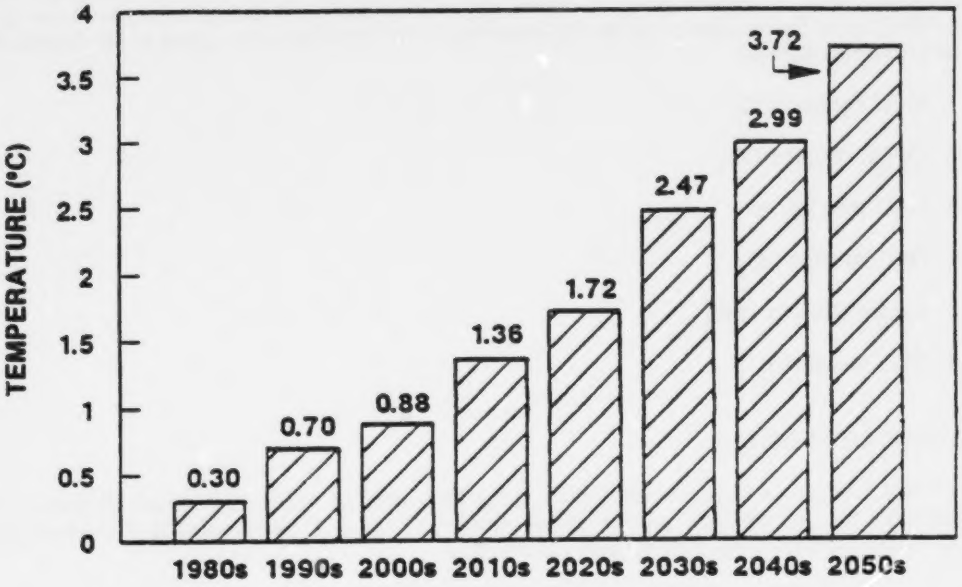
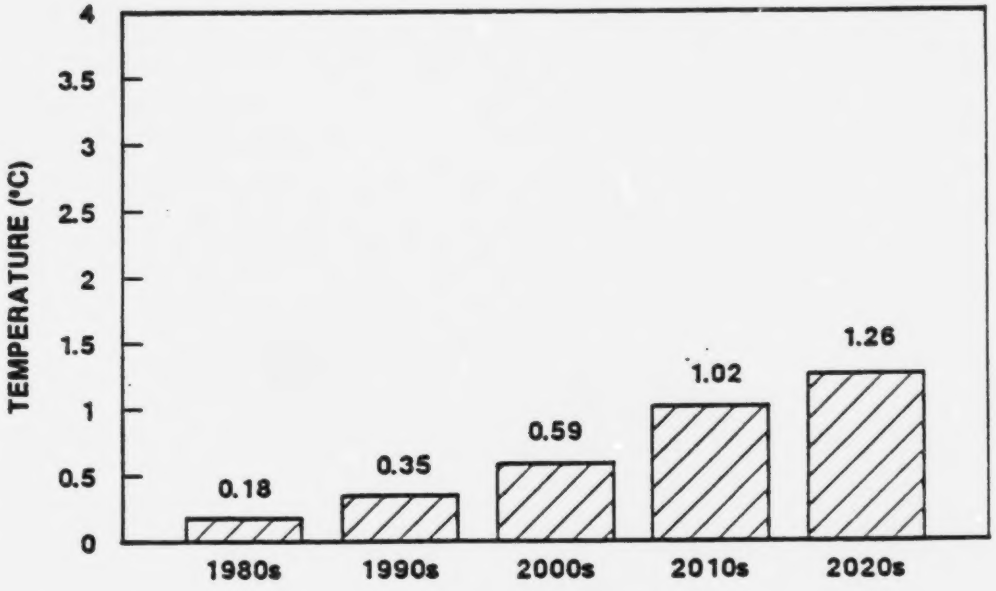


TRANSIENT SCENARIO A



TRANSIENT SCENARIO B

FIGURE 3. GISS TRANSIENTS "A" AND "B" AVERAGE TEMPERATURE CHANGE FOR LOWER 48 STATES GRID POINTS.

EPA specified that researchers were to use three doubled CO_2 scenarios, two transient scenarios, and an analog scenario in their studies. Many researchers, however, did not have sufficient time or resources to use all of the scenarios. EPA asked the researchers to run the scenarios in the following order, going as far through the list as time and resources allowed:

1. GISS doubled CO_2
2. GFDL doubled CO_2
3. GISS transient A
4. OSU doubled CO_2
5. Analog (1930 to 1939)
6. GISS transient B

ABOUT THESE APPENDICES

The studies contained in these appendices appear in the form that the researchers submitted them to EPA. These reports do not necessarily reflect the official position of the U.S. Environmental Protection Agency. Mention of trade names does not constitute an endorsement.

ASSESSING THE RESPONSE OF VEGETATION TO FUTURE CLIMATE CHANGE: ECOLOGICAL RESPONSE SURFACES AND PALEOECOLOGICAL MODEL VALIDATION

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FINDINGS[1]

Climate and vegetation models can be combined to assess how natural vegetation might respond to trace-gas-induced climate change. We used paleoclimatological and paleoecological data to test the ability of (1) atmospheric general circulation models (GCMs), (2) ecological response surface models, and (3) a forest-stand model to simulate observed past and present vegetation. Our results suggest that these models can be used to describe the broad-scale (10^5 to 10^6 km^2) equilibrium response of vegetation to past and therefore future climate change. Model simulations suggest that significant climate warming across this region is likely in all seasons. Our results suggest that this warming alone is sufficient to cause large-scale geographic shifts in plant populations and in total forest biomass. Even the most modest simulated warming is sufficient to cause significant vegetation change. Future precipitation changes are more difficult to assess, but could exacerbate future vegetation change.

We used two independent vegetation models coupled with three independent GCM scenarios to assess the response of natural vegetation to future climate change. The results of these different modeling efforts are in general agreement. Both the spruce-rich boreal forests and mixed conifer-hardwood forests of the Great Lakes and New England regions could be significantly altered by future climatic change. Spruce, fir, and pine populations could decline dramatically in these regions and could be replaced by larger populations of oak and other deciduous trees. The simulated eastward expansion of prairie forb populations south of the Great Lakes coincides with simulated decreases in total forest biomass. Vegetation change in the southeast U.S. could be large, but the nature of this change is difficult to assess because the projected extreme warmth in that region has no modern analogs. The range boundaries of southern pine populations could extend northward.

Our model validation efforts suggest that the current generation of climate and vegetation models can help in assessing the broad-scale equilibrium response of vegetation to climate change. Our validation of the models also demonstrates, however, that new research is needed before we can hope to simulate many details of future climate and vegetation change.

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[1] Although the information in this report has been wholly or partly funded by the U.S. Environmental Protection Agency under Interagency Agreement No. DW80932629-01, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

CHAPTER 1

INTRODUCTION

Current projections suggest that the concentration of radiatively active trace gases in the atmosphere could double their pre-industrial levels within 100-200 years. This change in an important climate boundary condition, and the climatic response (warming) to this change, have no analog in the past 18,000 years. This lack of a historical or geological analog means that we must rely on sophisticated numerical climate and vegetation models to predict future climatic change and its impact on vegetation. In order to trust the predictive accuracy of these models, we must test their ability to simulate realistic responses to large changes in climatic boundary conditions. Although the past does not contain an analog for doubled atmospheric trace gas concentrations, it does contain evidence of many large and complex changes in other boundary conditions (e.g., glacial-ice volume, insolation, and sea-surface temperatures). The validation of climate and vegetation models can be accomplished via the comparison of simulated and observed changes in climate and vegetation patterns of the past. This report uses this approach to lend confidence to our model results that suggest future climate-induced vegetation change in eastern North America could be significant.

In this report, we describe our efforts to simulate past and future vegetation change by coupling a number of General Circulation Models (GCMs) with two different types of vegetation model: (1) empirical response surfaces, and (2) a stand-simulation model. We compare simulations of past vegetation change directly with the observed geological record of vegetation change. The use of this paleoenvironmental data is key because it expands our matrix of "observed" climate and vegetation to include observations reflecting the response of the climate system to the changing boundary conditions of the past 18,000 years. In light of the large boundary condition change (i.e., atmospheric trace gases) that is likely to occur in the future, it is crucial that models be tested in a framework of changing boundary conditions and not just against 20th century observations. Our work thus constitutes an important step toward the systematic validation of climate and vegetation models that are being used for future impact assessment.

The use of records of past climate and vegetation change to improve the performance of models is an active area of research. Simulated climates are compared with climates reconstructed from geological data. Alternatively, simulated paleoclimate can be input into vegetation models (both empirical and dynamic) to yield simulated paleovegetation that can then be compared with observed paleovegetation data (e.g., fossil pollen data). Initial research has demonstrated that GCMs simulate some of the general patterns in the observed climate and vegetation record of the past 18,000 years. Our work complements data-model comparisons done to date at GISS, the 18,000-year B.P. experiments done at GFDL, and the more extensive COHMAP effort involving a NCAR GCM (Barnosky et al., 1987; Broccoli and Manabe, 1987; COHMAP, 1988; Hansen et al., 1984; Kutzbach and Guetter, 1986; Kutzbach, 1981; Kutzbach and Wright, 1985; Manabe and Broccoli, 1977; Overpeck et al., 1988; Rind, 1986; Rind et al., 1986; Rind and Peteet, 1985; Schneider et al., 1987; Webb et al., 1987; Wright, 1987). More importantly, this data-model comparison has led to improvements in our understanding of the climate-vegetation system and in the way we model these systems (Webb et al., 1987; Overpeck and Cook, 1988; Solomon and Shugart, 1984).

The record of climate and vegetation change over the past 18,000 years offers more than a unique opportunity for model validation. This paleoclimate/paleovegetation record also shows how vegetation responded to climatic change as large as that expected in response to increased atmospheric trace gases. For example, the record of late Quaternary vegetation change indicates that: (1) climate induces large spatially coherent patterns of change in the vegetation; (2) species respond individualistically to climate change; (3) the composition and structure of vegetation regions (e.g., biomes) vary temporally; (4) vegetation regions commonly appear, change, and disappear through time; and (5) climates unlike the present-day can occur and may result in vegetation assemblages unlike those of today (Gaudreau and Webb, 1985; Huntley and Webb, 1988; Jacobson et al., 1987; Overpeck et al., 1985; Overpeck and Cook, 1988; Webb, 1987). In this report, we use ecological response surfaces and a dynamic forest stand simulation model as two independent methods for modeling this type of observed climate-induced vegetation change.

Ecological response surfaces represent a method for quantifying the equilibrium relationship between climate and vegetation (Austin et al., 1984; Bartlein et al., 1986). In contrast to climate-vegetation classification schemes that relate the distribution of entire vegetation regions to climatic indices (e.g., Emanuel et al., 1985; Holdridge, 1947; Koppen, 1931), response surface methods help identify and model the relationships between individual plant taxa and climate. We use response surfaces to model the relationship between plant abundances and climate, but a similar approach may be used to model plant growth (Graumlich and Brubaker, 1986) or other aspects of plant biogeography. A focus on plant abundances is particularly appropriate when modeling vegetation at the regional to subcontinental (10^5-10^6 km^2) scale, which is close to the lower resolving limit of GCMs. After presenting a new set of response surfaces, we document that they can be used to simulate modern vegetation patterns. We then couple the response surfaces with GCM scenarios of $2xCO_2$ climate to obtain a new assessment of how vegetation could change in eastern North America. We obtain an independent assessment of future change using a dynamic forest stand simulation model (Solomon, 1986). The forest stand approach has been used with success before to simulate climate-induced vegetation change (e.g., Shugart, 1984; Davis and Botkin, 1985; Solomon et al., 1984; Solomon, 1986). In our study, the results of the stand modeling complement and support the results obtained using response surfaces.

After presenting the $2xCO_2$ modeling results for the two independent vegetation models, we test the accuracy of the models by simulating past vegetation change and then comparing the simulated results with maps of observed fossil pollen abundance. We demonstrate that vegetation change of the past was complex, but that the GCMs and response surfaces can be used to simulate many aspects of this past change. We also extend this model validation step to test the performance of the stand simulation model. Although these analyses reveal that the models can simulate many of the aspects of observed vegetation change, they also highlight the need for model improvement, additional paleoclimate/paleoecology research, and an expanded model validation effort.

CHAPTER 2

DATA AND STUDY AREA

Four principal types of data were used in our study of vegetation-climate interactions: (1) present-day observed climate data, (2) present-day observed vegetation data, (3) paleovegetation data for the past 18,000 years, and (4) simulated climate data for the past 18,000 years and for the 2xCO_2 world (ca. 2100 AD). The present-day climate and vegetation data were used to generate ecological response surfaces which were then combined with simulated climate data to yield simulated vegetation maps for selected periods of the past 18,000 years and for the 2xCO_2 world. Simulated climate was also used as input to a stand simulation model to yield a second set of simulated vegetation maps. We were able to assess the performance of the climate and vegetation modeling by comparing the maps of simulated paleovegetatation data with maps of observed paleovegetation data. This model validation step is crucial because it represents the only way to check how well climate and vegetation models can simulate observed vegetation and climate change when forced by changes in climatic boundary conditions.

Eastern North America (Figure 1) is ideal for the study of long-term climate-vegetation interactions for several reasons. The subcontinental scale of eastern North America closely matches the relatively coarse resolution of the models being used to simulate past and future climate. Climate and vegetation data are available in greater number for this region than any other comparably sized region in the world. This is true for the recent observational period as well as for the past 18,000 years. The changes of climate and vegetation in this region have been studied extensively and are relatively well understood. The eastern North American region therefore makes an excellent study area for use in the development and testing of climate and vegetation models.

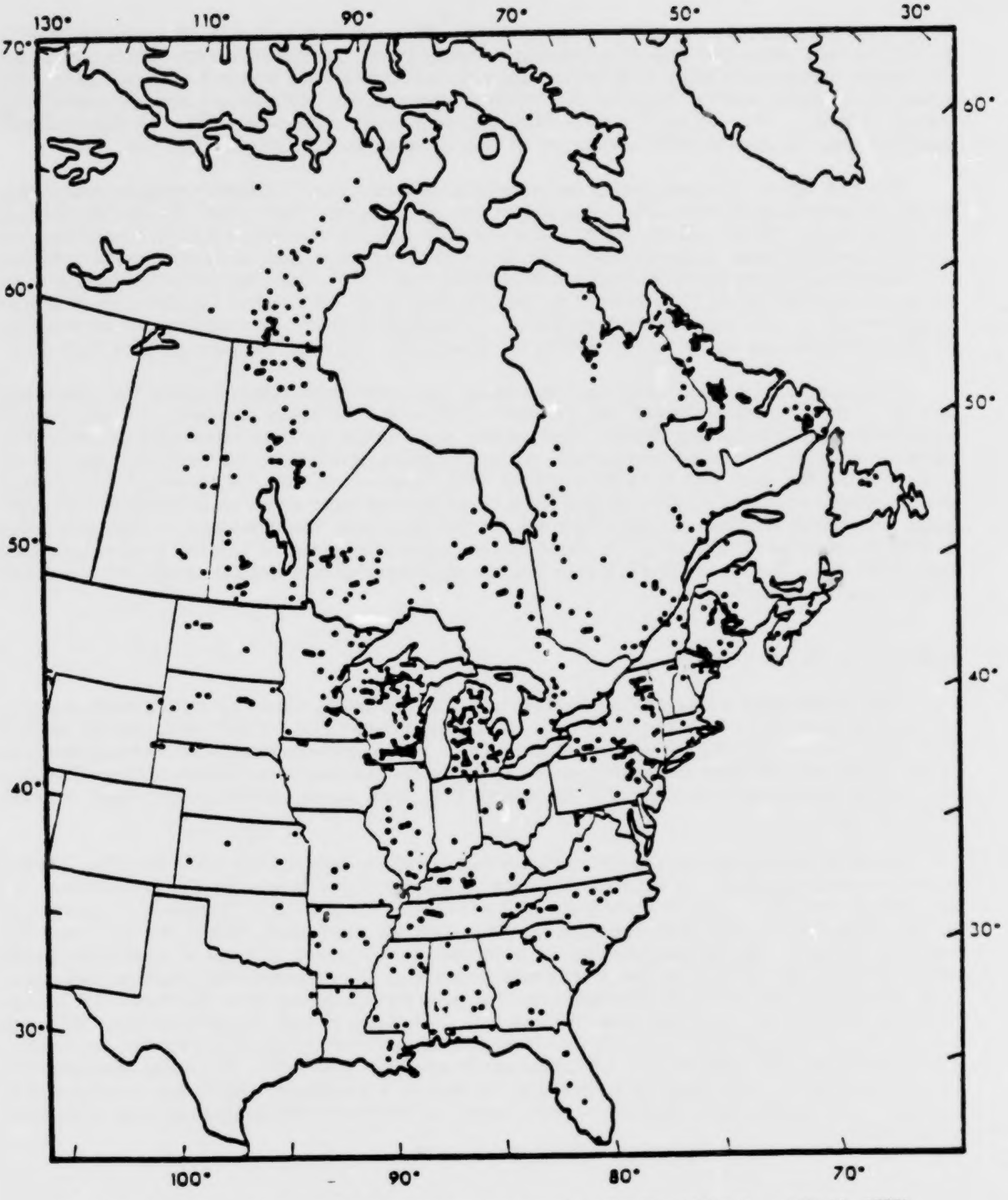
OBSERVATIONAL CLIMATE DATA

The period 1951-80 was used for the calculation of present-day climate normals. The eastern North American observational network for this period is quite dense, particularly in the U.S. portion of the region. We used an inverse-distance-weighting method to interpolate climate from 1328 U.S. observational stations to a 100-km equal-area grid. In most cases, a 100-km search radius was used in this interpolation, guaranteeing the averaging of at least 3 stations at each of the 416 U.S. grid points. In 51 cases, the lack of nearby stations necessitated a slightly larger search radius (maximum = 200 km, although most were close to 100 km). Gridded data were used because spatial data inhomogeneity and local outliers could bias ungridded data. The gridding also facilitated machine map contouring. Duplicate analyses with ungridded data were found to be more noisy, but essentially the same (Webb et al., 1987).

Time constraints required that we not use original station data from Canada. Instead, we digitized data from the National Climatic Atlas of Canada (1951-80 normals). Comparison of our digitized data with available station data for Canada indicated that digitizing errors were not significant. Further work will include the gridding of original Canadian station data as we did with the U.S. data. However, this task will be complicated by the low station coverage north of 50°N.

MODERN AND FOSSIL VEGETATION DATA

Vegetation data for eastern North America are extensive and available in several forms. We chose to work first with pollen data, but later we hope to expand our analyses to utilize complementary Continuous Forest Inventory data (Olson et al., 1980) and species range data (Little, 1971). In this report, we concentrate on pollen data for two principal reasons. First, the pollen samples in our database (Figures 1 and 2; Avizinis and Webb, 1983; Delcourt et al., 1984; Jacobson et al., 1987; Webb and McAndrews, 1976) provide representative abundance data for the entire eastern North American region. Over 800 samples of pollen from the surface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100°
90°
80°
70°

Figure 1. Locations of lakes and mires with modern samples of pollen (Avizinis and Webb, 1983).

sediments of lakes and mires are available from all the vegetation regions of eastern North America (Figure 1). Second, the use of pollen data enabled us to compare simulated taxon distributions directly with observed taxon distributions reconstructed using fossil pollen data from radiocarbon-dated lake and mire sediments. The available fossil pollen database consists of over 10,000 samples from over 250 lakes and mires in eastern North America (Figure 2). We used standard curve fitting and interpolation between the radiocarbon-dated sediment samples to generate maps of pollen abundances for selected time intervals (Overpeck and Fleri, 1982).

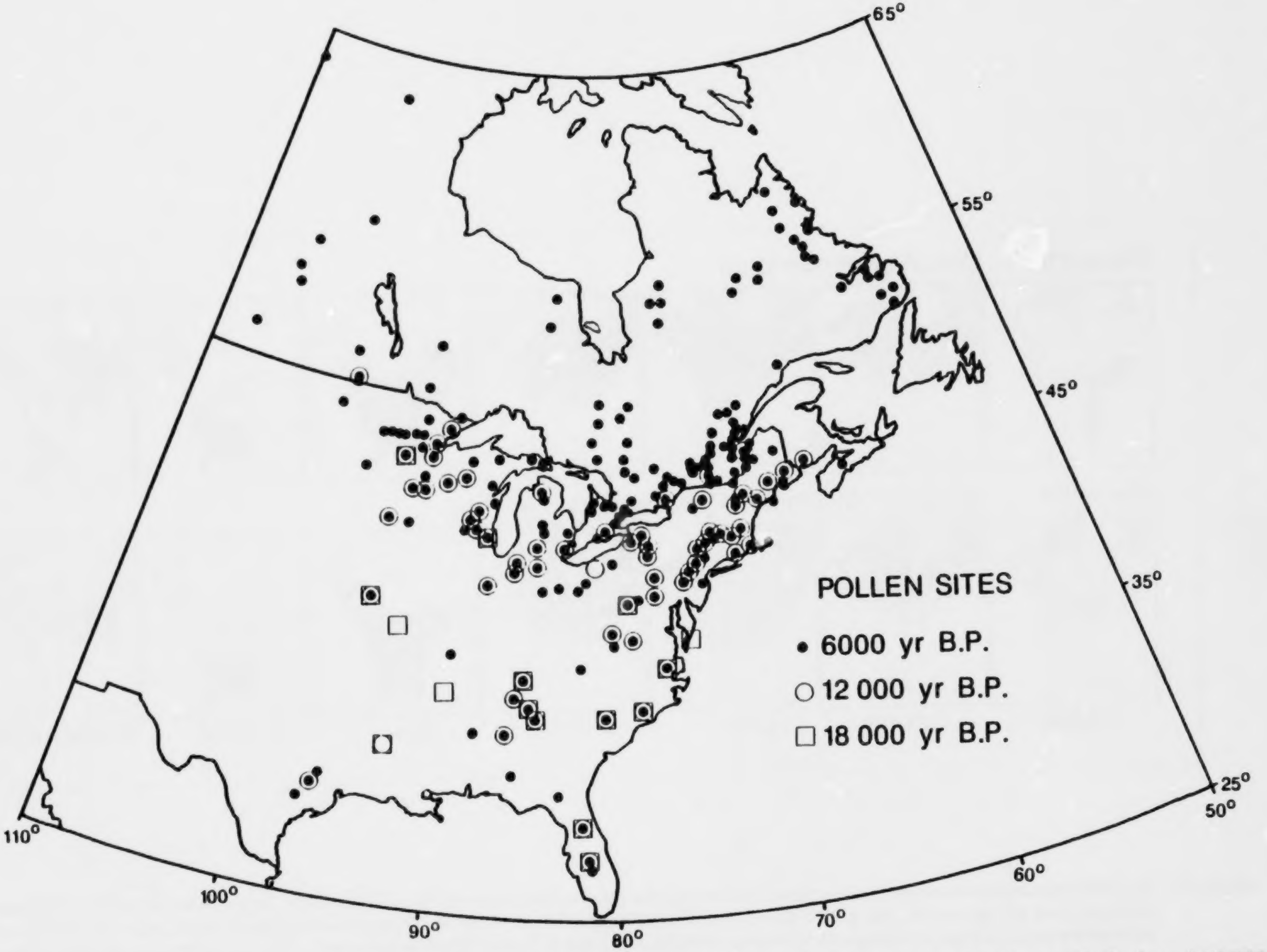
We were able to represent many of the broad-scale patterns of past and future vegetation change using the relative abundances of seven pollen types: sedge (Cyperaceae), spruce (Picea), birch (Betula), the northern and southern pines (Pinus), oak (Quercus), and prairie forbs (the sum of sage (Artemisia), Compositae, and pigweed (Chenopodiaceae-Amaranthaceae)). The northern pines were separated from southern pines by dividing the contemporary distribution of pine pollen at 40°N (Webb et al., 1987). Following the convention of previous studies (Bernabo and Webb, 1977; Webb et al., 1987; Jacobson et al., 1987), we used a pollen sum of all tree, shrub, and herb pollen to calculate pollen percentages. These previous studies have documented how well maps of pollen abundance display the modern distribution of vegetation across eastern North America (Figure 3).

Although the biome-scale patterns in vegetation can be reconstructed using pollen data, the relationships between plant and pollen abundances are not usually one-to-one. The pollen production rate and dispersal ability varies significantly among different plant species. Some species are under-represented by their pollen, whereas other species can be over-represented. Fortunately, pollen representation has been well studied (Webb et al., 1981; Delcourt et al., 1984; Bradshaw and Webb, 1985; Prentice et al., 1987), and the relationships between tree and pollen abundances are approximately linear for the five tree pollen types used in this study. The plant-pollen relationships for sedge and prairie forbs are less well understood. Our procedures for simulating pollen abundances via response surfaces and for reconstructing past vegetation can be extended to more than these seven pollen types (Bartlein and Webb, in prep.), but not all plants produce or disperse enough pollen to permit effective quantitative analysis.

SIMULATED CLIMATE DATA

Output from three different GCMs was used as equilibrium 2xCO_2 climate for eastern North America: (1) the GISS Model II 8°x10° GCM (Hansen et al., 1983, 1984); (2) the GFDL 4.4°x7.5° GCM, and (3) the OSU 4°x5° GCM (Ghan et al., 1982; Schlesinger and Zhao, 1988). These model experiments are described elsewhere in this volume, and differ from each other in several respects other than resolution. Because of these differences and different sensitivities to a doubling of atmospheric CO_2, these models provide a useful range of future climate scenarios.

No coordinated set of past, present, and future experiments has been run with any single GCM. For this reason, we used output from two additional GCMs for the purpose of climate/vegetation model validation: (1) the GISS Model II 4°x5° GCM (Hansen et al., 1983) and (2) the NCAR 4.4°x7.5° Community Climate Model (CCM) (Pitcher et al., 1983; Ramanathan et al., 1983; Kutzbach and Guetter, 1986). We used these two additional GCMs to simulate paleoclimates for a number of past periods in order to explore intermodel differences and to see how well the models performed given a range of climatic boundary conditions unlike those of the present-day. Systematic model testing of this type began with simulations of the 18,000-year B.P. Ice Age Maximum by the CLIMAP research group (Williams et al., 1974; Gates, 1976a,b; Manabe and Hahn, 1977), and has been expanded significantly by the COHMAP and GISS groups (Webb et al., 1985; Kutzbach and Guetter, 1986; Webb et al., 1987; Hansen et al., 1984; Rind and Peteet, 1985; Rind, 1986). The recent development of response surfaces for pollen data was motivated by the need for a quantitative method that could be used to compare observed paleoclimate data directly with climate data simulated by GCMs (Bartlein et al., 1986; Webb et al., 1987).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55°
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50°
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70°
80°
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100°
110°
POLLEN SITES
• 6000 yr B.P.
○ 12 000 yr B.P.
□ 18 000 yr B.P.

Figure 2. Locations of lakes and mires with pollen data for 6,000-years B.P. (black dots), 12,000-years B.P. (open circles), and 18,000-years B.P. (open squares). Many sites with pollen data at 6,000-years B.P. contributed data back to ca. 10,000-years B.P., and most sites contributed data form the mapped dates to the present (from Jacobson et al., 1987).

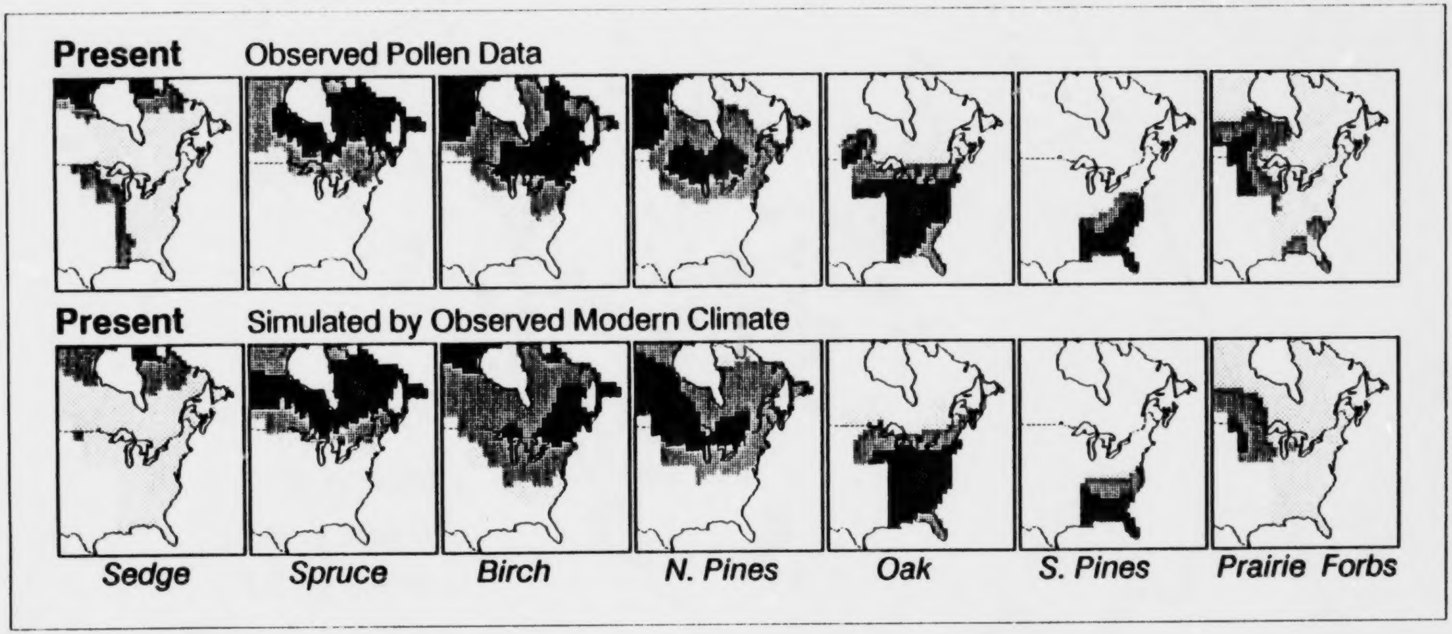

Present
Observed Pollen Data
Present
Simulated by Observed Modern Climate
Sedge
Spruce
Birch
N. Pines
Oak
S. Pines
Prairie Forbs

Figure 3. Isopoll maps of observed and simulated modern pollen percentages for seven pollen taxa. The observed pollen data maps were constructed using more than 1,200 samples of modern pollen (Figure 1). Response surfaces were used to obtain simulated estimates of pollen abundance using modern climate values of mean July temperature, mean January temperature, and annual precipitation. These estimates were then machine contoured. Three levels of shading indicate pollen percentages greater than 1% (lightest), 5%, and 20% (darkest). Portions of the grid without sufficient data were not mapped.

Global average temperature change over the past 18,000-year glacial to interglacial interval was approximately 4°C (Kutzbach and Guetter, 1986), similar in magnitude to the change anticipated in response to a doubling of atmospheric trace gas concentrations. Although this past period was obviously not a strict analog for the future, it does provide the only opportunity to perform rigorous tests of how well climate and vegetation models can simulate change as large as that expected in the future (Overpeck and Cook, 1988). For this reason, we used GCM simulations of the past 18,000 years.

NCAR CCM experiments for four time slices (18,000, 12,000, 9000, and 6000-years B.P) were used to simulate how the climate of eastern North America changed in response to changing solar radiation, sea surface temperatures, glacial ice extent and height, sea ice extent, and atmospheric trace-gas concentrations (Kutzbach and Guetter, 1986; Kutzbach, 1987). The CCM experiments used in this report are updated versions of those described in Kutzbach and Guetter (1986), and include experiments with longer run integration times and improved boundary conditions. The 18,000-year CCM experiment was rerun to incorporate a more realistic glacial ice height (20% lower than in the 1986 runs) over North America. The CCM experiments were not run with the full annual cycle. Instead, these model runs were run for January and July only. Kutzbach and Guetter (1986) determined that these "perpetual" January/July experiments can adequately approximate annual-averaged climate.

Because the annual cycle was not simulated in these experiments, we could not use CCM output as input to the stand simulation model. The GISS experiment differed in that it was run only for 18,000-year B.P., but with the full annual cycle. The 4°x5° GISS GCM was run with standard CLIMAP Ice Age boundary conditions (similar to those used in the NCAR CCM 18,000-year B.P. run). Altogether, the paleoclimate GCM experiments provide a clear view of how well these models, when coupled with available vegetation models, can simulate observed vegetation patterns of the past.

Modern (0-year B.P.) "control" GCM experiments all exhibit systematic biases when compared to observed modern climate (Schlesinger and Mitchell, 1987; Rind, 1986; Webb et al., 1987). In order to minimize the potential effects of these biases in our analyses, we used simulated climate anomalies ($2xCO_2$ or paleoclimate experiment minus control experiment) applied to the observed modern climate values. Climate values simulated by the GCMs therefore were not used directly.

CHAPTER 3

MODELING METHODS

EMPIRICAL ECOLOGICAL RESPONSE SURFACES

The distribution of vegetation on the landscape is related to a number of endogenous and exogenous processes (White, 1979; Shugart, 1984). Over sufficiently long time scales (102 to 106 years), the dominant influence of vegetation is climate (Webb, 1986). It is for this reason that modern ecotones are broadly coincident with the borders of climatic regions and that the abundances of plant species appear to have tracked favorable environments throughout the late Quaternary (Webb, 1986). Ecological response surfaces represent an effective way to quantify the manner in which a plant taxon's expected abundance (the response variable) depends on the combined effects of several environmental predictor variables (Bartlein et al., 1986). Ecological response surfaces can thus describe the equilibrium relationship between climate and the abundances of a particular taxon.

Bartlein et al. (1986) and Bartlein and Webb (in preparation) describe the theory and application of response surface methods to pollen data. Conceptually, the construction of a response surface represents the transformation of taxon abundances in geographic space to taxon abundances in climate space, where climate is defined as two or more climate predictor variables (Figure 4). For this study, we developed response surfaces for seven pollen types (spruce, northern pines, birch, southern pines, oak, sedge, and prairie forbs) using three climate variables (mean July temperature, mean January temperature, and mean annual precipitation) as predictors. These three climate variables represent the combined general effects of summer warmth, winter temperature stress, and moisture availability on plant abundances. We have begun to explore the potential for other seasonal climate variables, but the results presented in this report would probably not be changed by the incorporation of additional predictor variables that are correlated with the three we used.

Ecological response surfaces are powerful because they are nonlinear functions describing how two or more climate variables jointly control the abundances of a plant taxon. We used various nonlinear variable transformations to allow for flexibility in surface shape and then generated the surfaces using local weighted-average regression (Bartlein et al., 1986; Webb et al., 1987). Best fitting surfaces were identified, estimated, and diagnosed using standard statistical procedures (Bartlein et al., 1986; Bartlein and Webb, in preparation). The resulting response surfaces for each of the seven pollen taxa are unique. The surfaces can be coupled with simulated values of mean July temperature, mean January temperature, and annual precipitation to yield estimates of simulated pollen abundances. This calculation was done using simulated climates from each GCM experiment at each of the locations with fossil data. Machine contouring yielded the finished maps of simulated pollen abundance.

FOREST STAND SIMULATION

Forest stand simulation models have been developed and described extensively (Botkin et al., 1972; Shugart and West, 1977; 1979; Shugart, 1984; Davis and Botkin, 1985). The FORENA model was developed from these earlier models expressly to simulate the forests of eastern North America (Solomon et al., 1984; Solomon, 1986). We coupled FORENA with three sets of climate data: (1) modern observed climate (1951-80) from our 100-km grid; (2) 2xCO_2 equilibrium climate simulated using the GISS 8°x10° GCM; and (3) 18,000-year B.P. climate simulated by the GISS 4°x5° GCM. The 2xCO_2 experiment was run to obtain a second independent assessment of how vegetation may change in the future, whereas the modern and 18,000-year B.P. experiments were run to explore how well a stand simulation model could reproduce observed vegetation patterns. In these experiments, we used Solomon's (1986) model with his relatively moisture-insensitive soil and with a modification that allowed the length of the growing season to vary with the simulated input climate. We

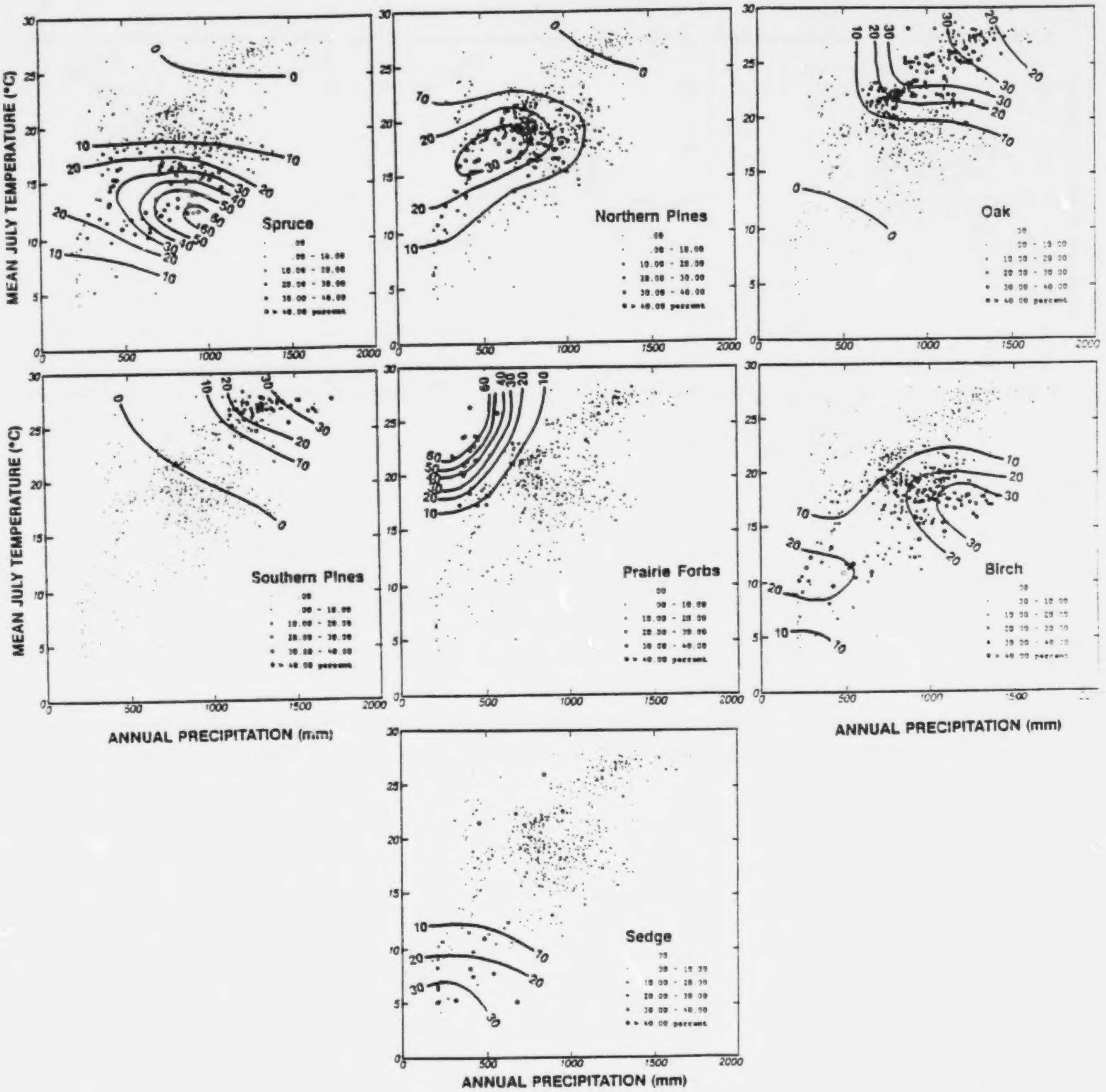


Figure 4. Response surfaces showing the relationship between the percentages of seven pollen types and three climate predictor variables: mean July temperature, mean January temperature, and annual precipitation. Two surfaces are plotted for each taxa for display purposes, but the two surfaces for each individual taxon were fit simultaneously using local weighted-average regression. The three-dimensional surfaces therefore extend over all the modern data.

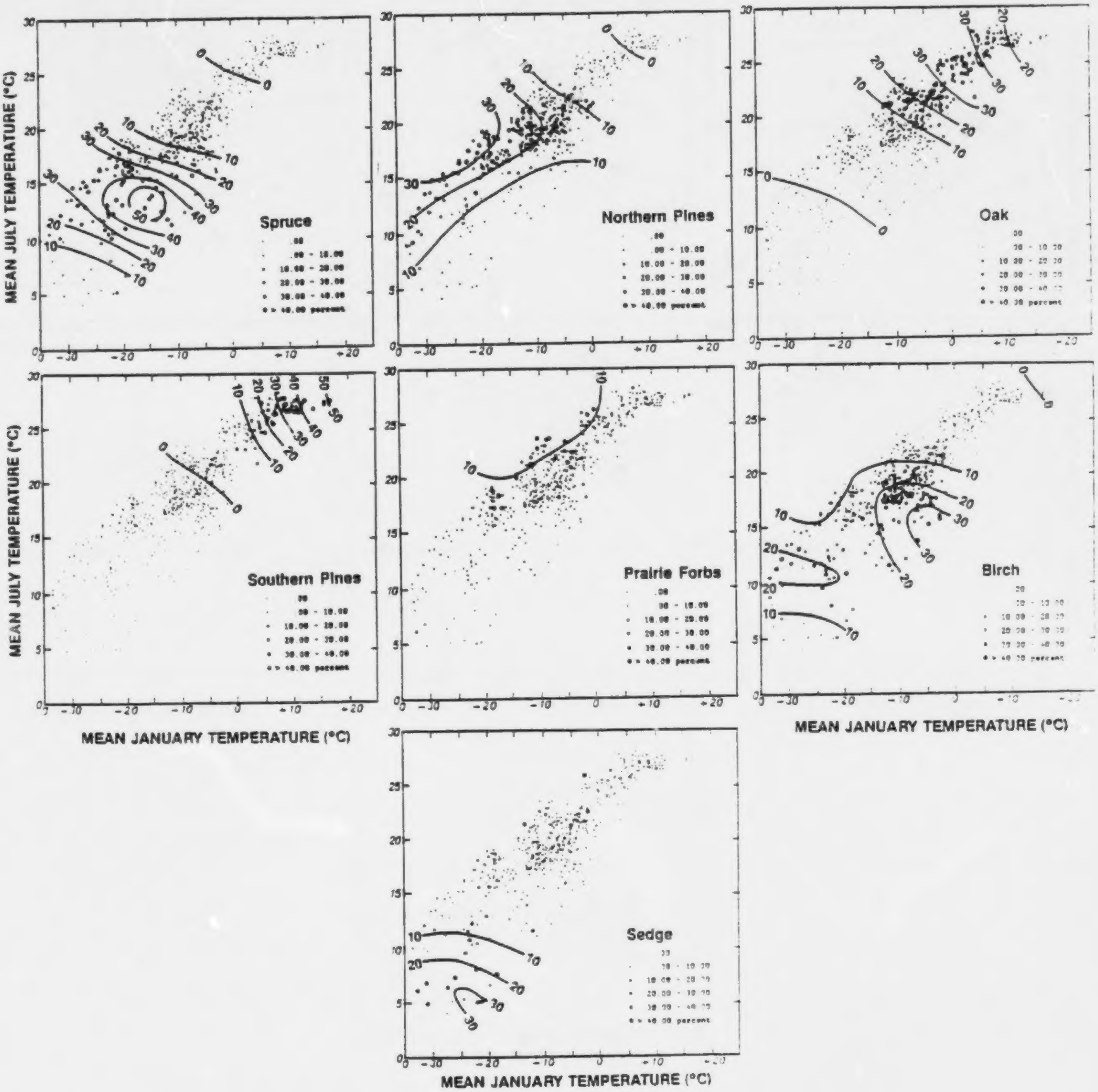


Figure 4. (continued)

simulated 20 forest plots at each of up to 40 equally spaced ice-free grid points in eastern North America (Figure 1). We found that the model correctly simulated no tree growth in areas of climatic extremes, including far northern areas and the prairie. We ran each simulation for 400 years, averaging tree abundances over the final 100 years to yield relativebiomass values at each of the grid points. The relative tree abundances for six tree taxa (spruce, pine, birch, oak, fir, and maple) were then mapped along with simulated total tree biomass.

CHAPTER 4

RESULTS

SIMULATED VERSUS OBSERVED MODERN VEGETATION PATTERNS

The fitted response surfaces for the seven pollen taxa portray how the abundances of these taxa relate to winter temperature, summer temperature, and annual moisture availability (Figure 4). Each surface is unique and reveals the optimum climatic conditions for a taxon. Steep gradients on a surface reveal where a taxon is most sensitive to a change in climate. In addition, the surfaces define the approximate locations in climate space of range boundaries for each of the seven taxa. The response surfaces clearly reveal patterns in the vegetation-climate relationship that are obscure when viewed in geographic space.

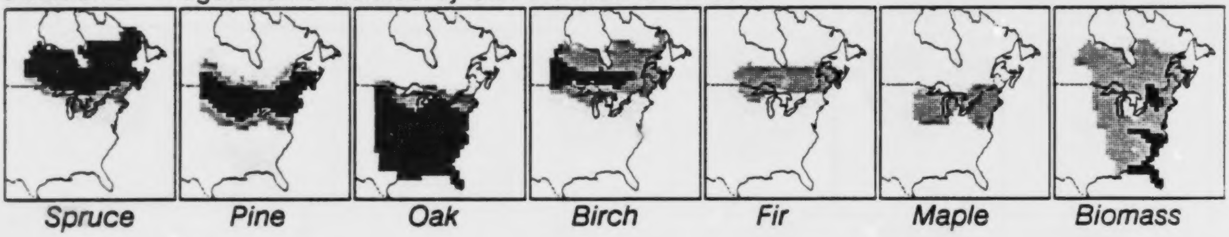
The major vegetational patterns of eastern North America are captured by the response surfaces. Sedge abundances are high in the cool dry portions of Canada, whereas the southern pines are favored in the warm moist southeast U.S. The surface for prairie forbs exhibits a steep gradient corresponding to the prairie-forest ecotone, a region that could be very sensitive to future climatic change. The surfaces for spruce, northern pines, birch, and oak all portray well-defined optima surrounded by gradients of varying magnitude and direction. Each of these taxa is susceptible to different combinations of climatic change. Altogether, the surfaces reveal that even slight climatic change can have a significant effect on natural vegetation.

When coupled with observed modern climate data, the response surfaces are able to simulate most of the patterns exhibited in maps of observed pollen data (Figure 3). High abundances of spruce presently are confined to the boreal forest of Canada, with sedge dominating the northernmost tundra areas. Two distinct birch populations appear on maps of simulated and observed pollen abundances. Shrub birch populations occur in the northern forest-tundra and tundra regions, whereas tree birch populations give rise to high birch pollen percentages in the boreal and mixed conifer-hardwood forests. The high abundances of oak and prairie forb pollen delineate the deciduous forest and Great Plains grasslands, respectively. The mapped patterns for both northern and southern pines show clear agreement and define the pine-dominated biomes (southeast pine forests, mixed conifer-hardwoods, and the western boreal forest). Quantitative measures of map association confirm that the simulated pollen maps reproduce most of the patterns in observed pollen abundance over North America (Webb et al., 1987). The only significant exception is the poor match of sedge abundances in the prairie, an anomaly probably induced by the high abundances of local wetland sedge populations.

Most of the same observed patterns in the modern vegetation of eastern North America are also reproduced by the stand simulation model (Figure 5). In general, the model simulated little or no tree biomass in areas presently characterized by treeless landscapes (e.g., the prairie and tundra). Simulated spruce abundances are high in the boreal forest along with moderate amounts of pine, birch, and fir. Too little fir is simulated in the northeasternmost part of the map area, and the amount of diploxylon pine in the northern boreal forest and southeast U.S. are underestimated by the stand model. Both northern hard maples and southern soft maples are simulated fairly well, as are oak populations. Whereas the stand model cannot simulate the abundances of nonarboreal taxa, such as prairie forbs or sedges, it does do a good job of simulating subcontinental scale patterns in the abundance of most tree taxa over eastern North America.

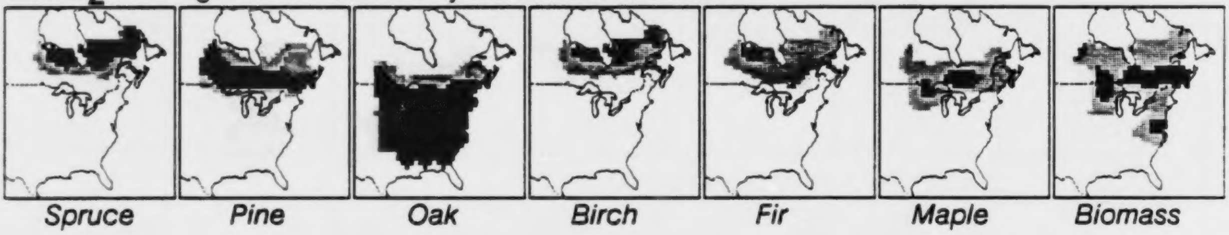
FUTURE VEGETATION CHANGE - 2xCO$_2$ SCENARIOS

Future equilibrium vegetation patterns were simulated using the output from three 2xCO$_2$ GCM experiments coupled with (1) the seven response surfaces and (2) the stand simulation model. The results from these two independent vegetation models are in agreement, and suggest that trace-gas-induced warming could cause significant change in natural vegetation over most of eastern North America (Figures 5 and 6). Large warming over all of this region in both summer and winter characterizes all three 2xCO$_2$ climate scenarios,



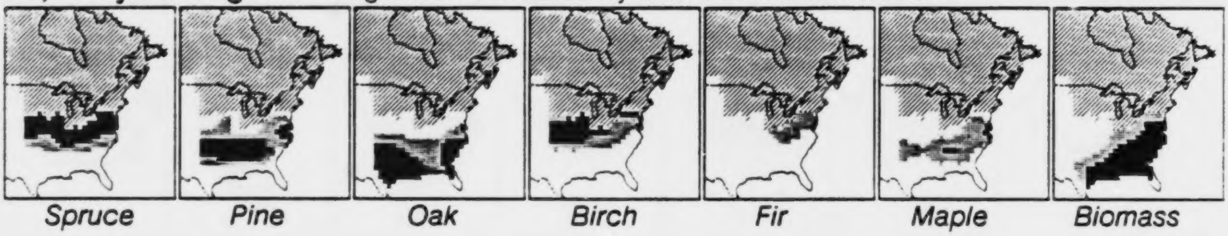
Present Vegetation Simulated by Stand Simulation Model

Spruce
Pine
Oak
Birch
Fir
Maple
Biomass



$2xCO_2$ Vegetation Simulated by Stand Simulation Model

Spruce
Pine
Oak
Birch
Fir
Maple
Biomass



18,000 years ago Vegetation Simulated by Stand Simulation Model

Spruce
Pine
Oak
Birch
Fir
Maple
Biomass

Figure 5. Vegetation patterns simulated with the forest stand model using (a) modern climate values, (b) the GISS $2xCO_2$ scenario, and (c) the GISS 18,000-year B.P. climate simulation. Biomass values (contoured less than 50 (lightest shading), 50 to 100, and greater than 100 (darkest)) are in megagrams of biomass per hectare, whereas the relative tree abundances are in percent (same shading as in Figure 3). In each case, the biomass map outlines the area in which vegetation could be simulated using the forest stand model (refer to the text for the reasons for this). The extent of the Laurentide Ice Sheet and associated glacial lakes is delimited by diagonal shading on the maps for 18,000-year B.P.

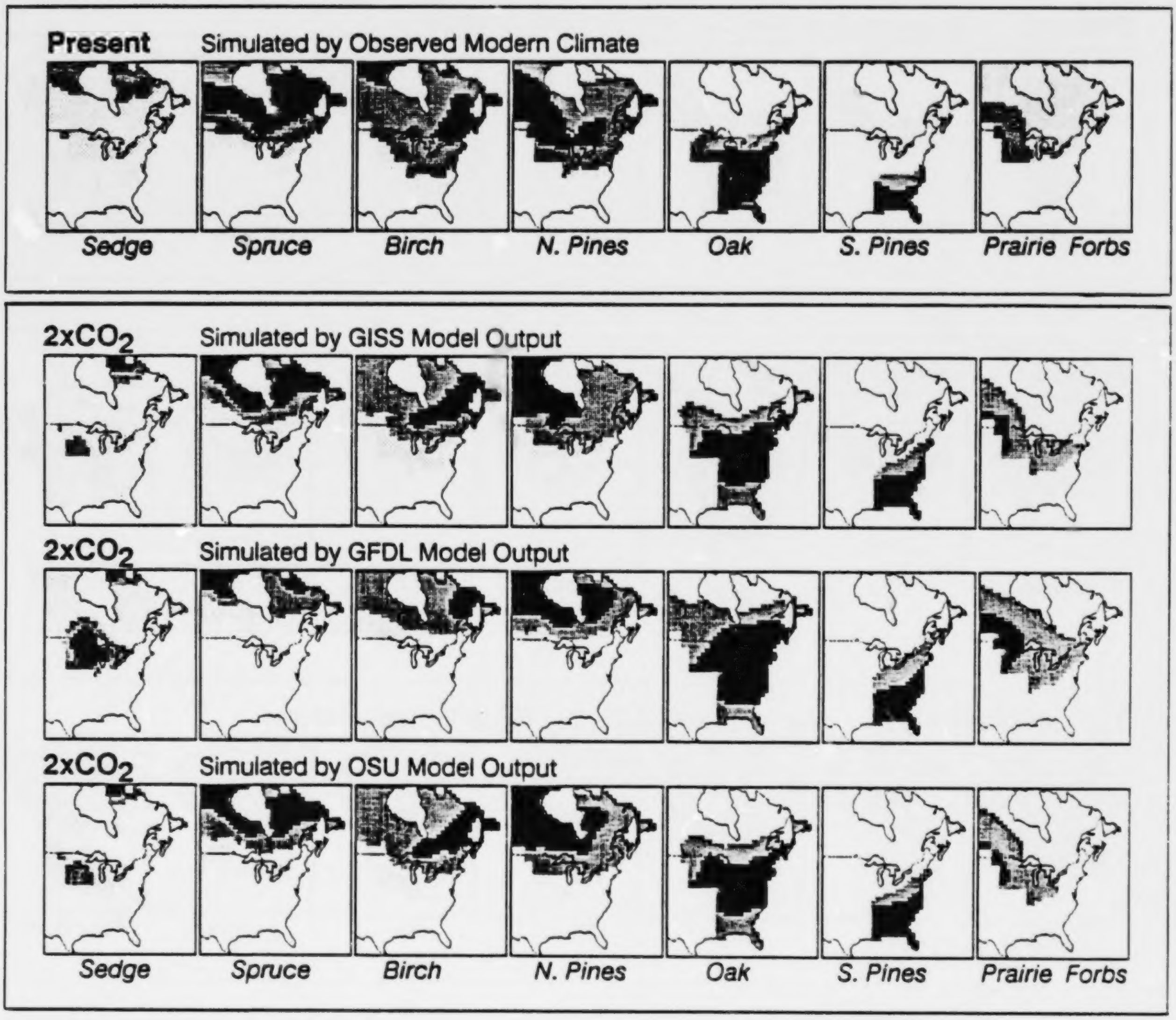

Present
Simulated by Observed Modern Climate
Sedge
Spruce
Birch
N. Pines
Oak
S. Pines
Prairie Forbs
2xCO2
Simulated by GISS Model Output
2xCO2
Simulated by GFDL Model Output
2xCO2
Simulated by OSU Model Output
Sedge
Spruce
Birch
N. Pines
Oak
S. Pines
Prairie Forbs

Figure 6. Simulated modern pollen abundances and simulated future pollen abundances for each of the three $2xCO_2$ scenarios: (a) GISS, (b) GFDL, and (c) OSU. Modern pollen abundances were simulated using instrumental climate data as input to the response surfaces shown in Figure 4, whereas the simulated $2xCO_2$ pollen abundances were generated using the same surfaces coupled with putput from the $2xCO_2$ climate scenarios. Shading is the same as in Figure 3.

whereas changes in simulated precipitation are more regional and less coherent among the models. Each of these climate scenarios produced patterns of vegetation change that are generally similar, thus suggesting that climate warming alone has the potential to cause significant future vegetation change. Our results also suggest that even modest climate warming (e.g., the OSU scenario) could lead to substantial changes in the natural vegetation of eastern North America.

Results generated using the response surface models suggest that components of all the major vegetation regions in eastern North America will move northward in response to increased summer and winter warmth (Figure 6). Model results suggest that spruce populations in the northeast U.S. will decline in abundance, as will populations of northern pines (P. strobus and P. resinosa). Areas now dominated by mixed conifer-hardwood forest could become increasingly deciduous in nature, particularly with large increases in oak abundance in the Great Lakes and New England regions. Response-surface results generated using the GISS GCM results suggest that the northward spread of oak could be further encouraged by drying at mid-latitudes. A large eastward expansion of prairie forb abundances across the northern U.S. is simulated by all three GCM scenarios, even in areas where simulated annual precipitation is greater than today (i.e., in the GFDL and OSU scenarios). Our results suggest that forest biomass could decline even without significant decreases in precipitation. The large simulated eastward expansion of prairie forb populations in the GISS scenario indicate, however, that regional drying could exacerbate the spread of xeric vegetation at the expense of more mesic vegetation.

In addition to the increase of dry/warm adapted taxa across the Great Lakes and northeast regions, the response surface results indicate that the U.S. could also experience a northward expansion of southern pine populations. Taxa that do poorly at the southern ends of their ranges (spruce and northern pines) all expand in abundance further north. Birch populations are notable because their areas of greatest abundance could contract significantly, changing the structure of the Canadian boreal forest. Tundra regions, marked by high abundances of sedge pollen, appear to suffer most west of Hudson Bay where simulated warming favors the expansion of tree populations. The broad agreement between vegetation patterns simulated in each of the three GCM scenarios suggest that anticipated changes in mean winter temperature, mean summer temperature, and mean annual precipitation could all contribute to significant vegetation change.

An independent assessment of possible future vegetation change was produced by coupling the FORENA forest stand simulation model with the GISS $2xCO_2$ climate scenarios (Figure 5). The broad agreement between the three climate scenarios and between the three response surface assessments (Figure 6) suggest that these stand simulation results are probably representative of those that could be generated using the other two GCMs. In general, the same major patterns of change that were produced by the response surface modeling and earlier forest stand modeling (Solomon, 1986) were reproduced by our forest stand simulations. Efforts to simulate forest growth at the southernmost grid points failed because the $2xCO_2$ climate was too warm for the model. This failure of the stand model to simulate southeast forests does not imply treeless vegetation. Instead, this failure suggests that future climate in the southeast could have no modern analogs and that the current generation of empirically based stand models is inappropriate for assessing future vegetation change in this region. The stand-model was not designed to simulate the many subtropical tree species that may end up growing in the southeastern U.S. To the north of this region, however, the forest stand model yields sound results and thus reinforces the possibility that trace-gas-induced climate change will cause large-scale northward shifts in the populations of many tree taxa.

The results of the stand modeling agree with many details of the response surface results. Populations of three dominant forest components, spruce, pine, and oak, might all contract in the southern portions of their ranges and expand in the north (Figure 5). With the possible exception of hemlock, most conifer populations in the Great Lakes and New England regions might be adversely affected, whereas populations of some hardwoods, notably oak, hickory, and perhaps maple could expand in these areas. The simulated trace-gas-induced warming also led to a modeled decrease of birch populations northward in the U.S., and an expansion of birch populations in Canada. Southern pine populations may also expand northward. Although it is difficult to assess the reliability of absolute forest biomass values simulated by the stand model, it is suprising that the $2xCO_2$ stand model results predict lower total biomass values across the same northern U.S. region that was characterized by an expansion of prairie forbs in the $2xCO_2$ response surface simulations. This result lends confidence to the assertion that trace-gas-induced warming and drying could contribute to significant decreases in total forest productivity as well as to important shifts in the species composition and structure of forests in eastern North America.

It is important to note that our use of response surfaces and the stand model implicitly assumes that the vegetation is in equilibrium with climate. The comparison of simulated and observed past vegetation data (see below, and Webb et al., 1987) indicates that vegetation has been able to track climate over the past 18,000 years. Future trace-gas-induced climatic change is expected, however, to be more rapid than the changes of the past 18,000 years. This raises the possiblity that the future time-dependent patterns of vegetation change could be different from those mapped in our equilibrium assessments (Figures 5 and 6). Our assessments show how vegetation patterns may look after sufficient time has elapsed for individual plant taxa to adjust fully to new climatic patterns.

PAST CLIMATES - MODEL VALIDATION

A major difficulty in simulating climate and vegetation of the past stems from our inability to specify accurately how climate boundary conditions change. This is particularly true for the deglacial interval 18,000 to 10,000-year B.P., when several boundary conditions (e.g., glacial ice height and extent, sea surface temperatures, sea ice extent, and atmospheric aerosols; see COHMAP, 1988) were changing rapidly. After 10,000-years B.P., the boundary conditions (including the seasonal distribution of solar radiation) were different from today, but the rate and complexity of change diminished, making it easier to specify the boundary conditions for the GCM experiments. Climate simulations for the interval from 10,000 to 0-year B.P. are thus likely to be more accurate than those for the preceding deglacial interval. It is in part for this reason that we have chosen to use a number of GCM sensitivity experiments, each with slightly different boundary conditions, to represent 18,000-year B.P. In addition to providing model validation opportunities, the data-model comparison described in this section helps to improve our understanding of how the climate system works.

Response Surfaces - The NCAR CCM

When coupled with our response surfaces, the NCAR CCM-simulated climate for 18,000-year B.P. yields maps of simulated pollen abundances that show some resemblance to observed pollen percentages (Figure 7). The abundances of spruce pollen are simulated fairly well, as is the absence of southern pine populations. With the exception of birch, the approximate ranges of the other taxa are also simulated satisfactorily. Observed abundance patterns within these ranges, however, are not simulated as well as might be hoped. These mismatches could be related to (1) the lack of dynamic equilibrium between vegetation and climate (Webb, 1986); (2) shortcomings of the response surfaces; (3) inappropriate rescaling of the coarse spatial resolution of the GCMs output to the scale of the individual fossil-pollen sites; (4) inaccuracies of the GCMs, due either to inadequate model design or poor specification of boundary conditions (Webb et al., 1987); or (5) changes in the model biases that could make the use of perturbation-minus-control model anomalies inappropriate. The improved performance of the models in simulating more recent (e.g., 9,000 to 0-year B.P.) vegetation argues that poor boundary condition specification may be the major reason for mismatch between earlier simulated and observed maps. The anomalously high abundances of simulated oak and prairie forb pollen at 18,000-year B.P., and low abundances of simulated northern pine pollen, suggest that the CCM simulation for the southeast U.S. was too warm (by 2°C) for this time period (Webb et al., 1987). The large observed abundances of prairie forbs at 18,000-year B.P. suggest that the climate simulated by the NCAR CCM may also be too dry for this period. Similar analysis using a GCM 18,000-year B.P. experiment with lowered sea surface temperatures may eliminate much of the mismatch between maps of simulated and observed pollen abundance.

The simulations for 12,000, 9,000, and 6,000-year B.P. show an increasing degree of match with maps of observed pollen abundances (Figures 8-10). Numerical measures of association between these two sets of maps

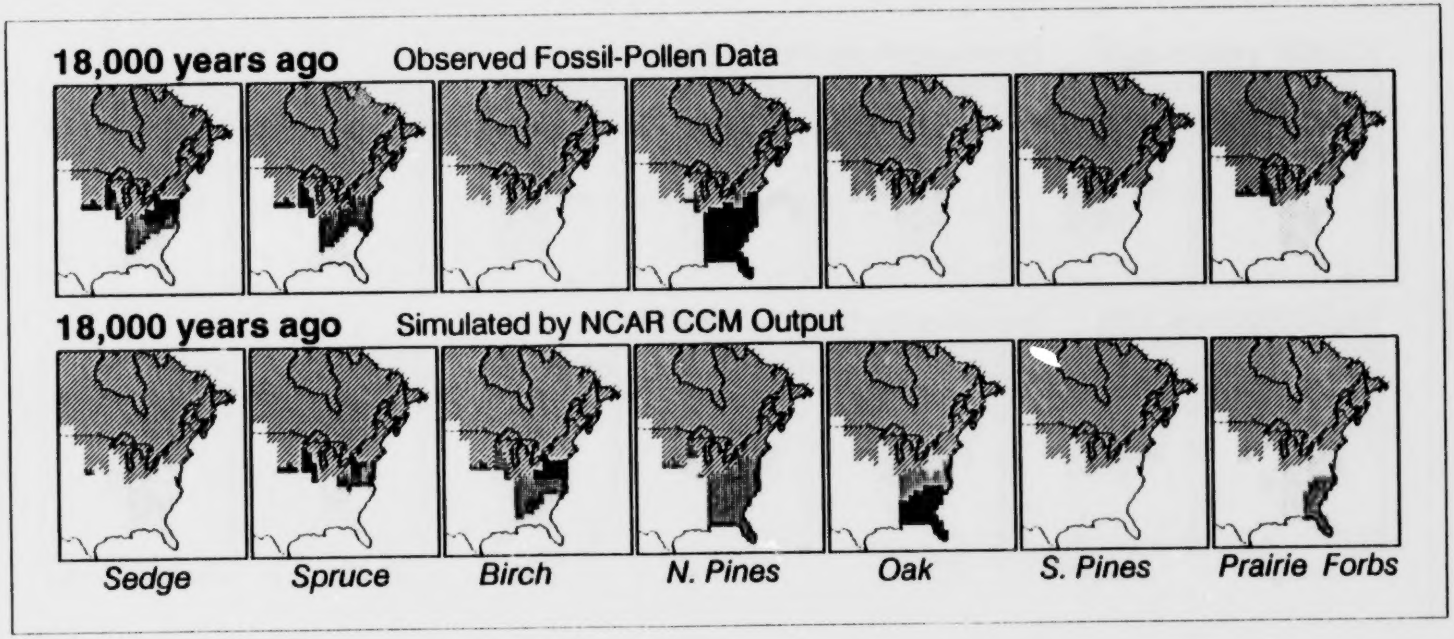

18,000 years ago
Observed Fossil-Pollen Data
18,000 years ago
Simulated by NCAR CCM Output
Sedge
Spruce
Birch
N. Pines
Oak
S. Pines
Prairie Forbs

Figure 7. Observed and simulated pollen data for 18,000-year B.P. Responses surfaces (Figure 4) and climate data from the NCAR CCM were used to produce the simulated pollen data. The shadings are as in Figure 3, except that the extent of the Laurentide Ice Sheet and associated glacial lakes are delimited by diagonal shading. Portions of the grid without sufficient data were not contoured.

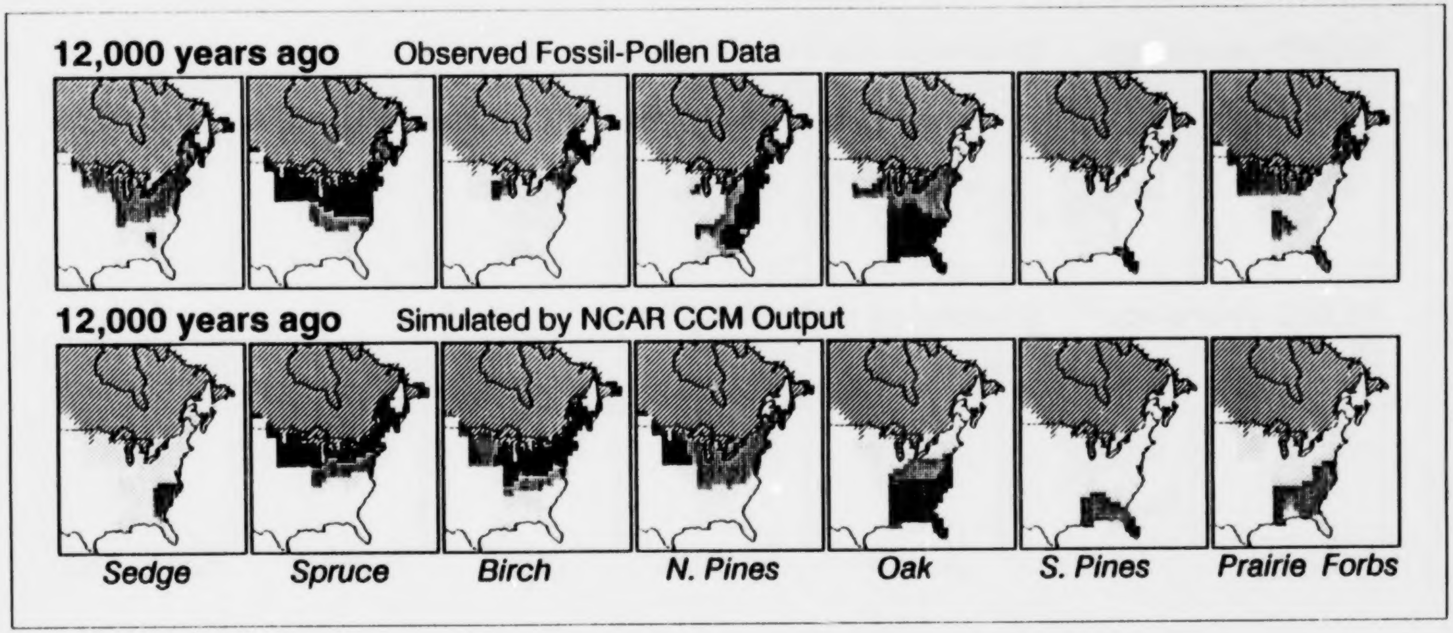
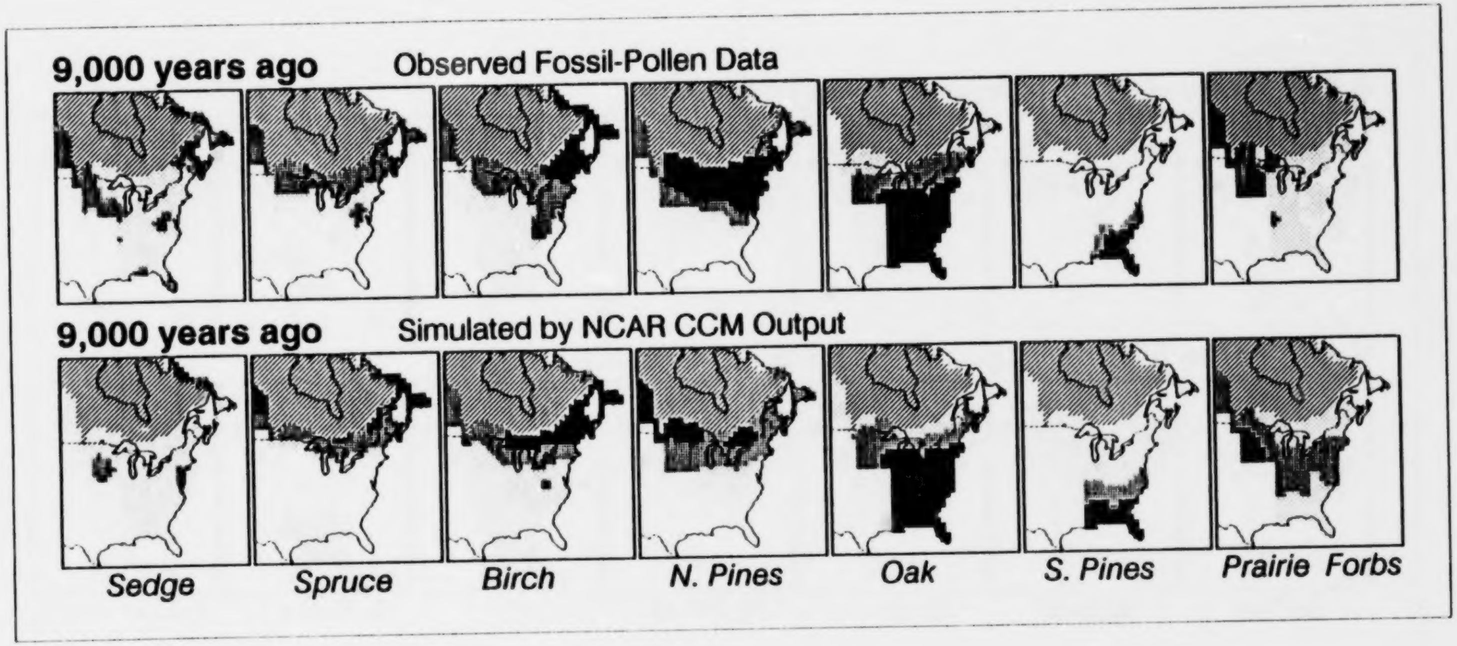

12,000 years ago Observed Fossil-Pollen Data
12,000 years ago Simulated by NCAR CCM Output
Sedge
Spruce
Birch
N. Pines
Oak
S. Pines
Prairie Forbs

Figure 8. Observed and simulated pollen data for 12,000-year B.P. See Figure 7 for details.



9,000 years ago
Observed Fossil-Pollen Data
9,000 years ago
Simulated by NCAR CCM Output
Sedge
Spruce
Birch
N. Pines
Oak
S. Pines
Prairie Forbs

Figure 9. Observed and simulated pollen data for 9,000-year B.P. See Figure 7 for details.

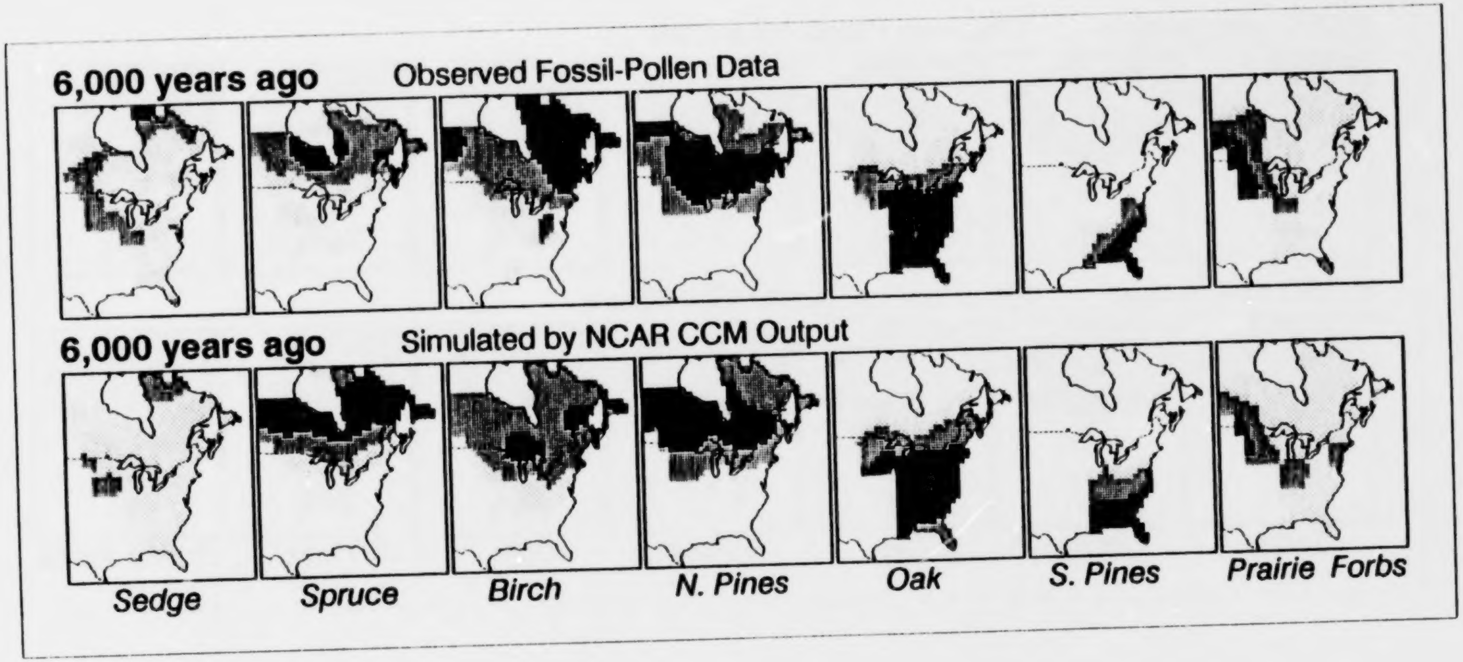

6,000 years ago
Observed Fossil-Pollen Data
6,000 years ago
Simulated by NCAR CCM Output
Sedge
Spruce
Birch
N. Pines
Oak
S. Pines
Prairie Forbs

Figure 10. Observed and simulated pollen data for 6,000-year B.P. See Figure 7 for details.

between simulated and observed pollen percentages is better than for earlier periods (Webb et al., 1987), and that the response surfaces coupled with GCM climate can do a good job of simulating observed patterns in the paleovegetation of eastern North America. This is a strong test of model performance, because the climate boundary conditions at 9,000-year B.P. were significantly different than the present-day (Kutzbach and Guetter, 1986). The simulated maps for spruce, birch, northern pines, oak, and southern pines all reproduce the observed individualistic response of these types to climate change during the interval from 12,000 to 0-year B.P. The simulations for sedge and prairie forbs fare less well, perhaps because of the GCM's inability to model precipitation as well as temperature, or in the case of sedge, because plants of these taxa are more likely to be responding to local site factors south of tundra regions than to regional macroclimate. The overall match between simulated and observed pollen percentages is encouraging, but these paleoclimatic results should also temper our efforts to attach significance to changes in simulated pollen abundance.

Stand Simulation Model - The GISS GCM

One of the major advantages of using pollen data as a proxy for vegetation is the ease with which simulated pollen data lends itself to comparison with observed paleovegetation (fossil pollen) data. Validation of the forest stand simulation model is more difficult than the response surface model because maps of relative biomass cannot be compared directly to maps of relative pollen abundances. Eventually, the relationships between pollen abundance and tree abundance may be quantified to the extent that these two can be compared directly in model validation experiments. In the meantime, however, it is still possible to obtain a qualitative assessment of how well the stand model works by comparing the broad patterns of simulated taxon ranges, abundance gradients, and optima with those in the maps of fossil pollen abundance (Figure 7).

Because the annual cycle was not simulated in the NCAR CCM experiments, we used the GISS GCM with similar 18,000-year B.P. boundary conditions to examine how well past vegetation patterns could be simulated using GCM output as input to the forest stand succession model (Figure 5). Like the NCAR CCM, the GISS model simulated a colder climate for 18,000-year B.P. In contrast, the NCAR CCM simulated a dry southeastern U.S. at 18,000-year B.P., whereas the GISS GCM simulated higher precipitation in this same region. This result is not suprising and reinforces the fact that we must be careful when using GCM output to make regional assessments. In any case, the stand simulation model appears to do less well than the response surfaces in modeling the 18,000-year B.P. vegetation patterns. The stand model is able to simulate high abundances of spruce and pine south of the Laurentide Ice Sheet and no tree growth in areas the fossil evidence suggest there were few trees. Although the stand model simulates the correct amount of these taxa at 18,000-year B.P., it overestimates the past abundances of some other taxa such as birch, oak, beech, ash, and chestnut. As we emphasized before, there are several reasons why simulated and observed vegetation patterns may not match. New GCM experiments with the annual cycle and improved specification of boundary conditions clearly need to be run in order to obtain a thorough validation of forest stand succession models.

CHAPTER 5

DISCUSSION

SIGNIFICANT RESULTS

Most assessments of future climate and vegetation change will center on the development and use of imperfect quantitative models. One primary component of this assessment process therefore must be to develop systematic methods for measuring the uncertainty in the models and for improving the models. For example, each of the GCMs presently used to simulate the $2xCO_2$ world yields a somewhat different view of our future climate. What parts of these simulated views can we trust? We already know that the differences among GCM simulations can be significant, particularly where hydrologic variables or finer geographic patterns are concerned (Schlesinger and Mitchell, 1987). The fact that we wish to model large climate or vegetation change implies that it is not sufficient to validate a model solely against modern observational data. An important result of our study is that paleoclimatic and paleovegetation data can form a central basis for assessing how well climate and vegetation models simulate change given boundary conditions unlike the present day (Schneider, 1986).

Our direct comparisons between observed paleovegetation (pollen) data and paleovegetation data simulated with GCMs and vegetation models suggest that we can begin to use these models to assess subcontinental to regional scale (10^5 to 10^6 km^2) patterns of future climate and vegetation change. This is the approximate resolution limit of current GCMs and the scale at which we were able to simulate observed patterns in fossil pollen data. Even at this scale, however, it is clear that some uncertainty exists. We cannot simulate the response of all plant taxa to future climatic change, nor can we simulate many processes that could influence future vegetation change. New climate and vegetation research will have to be conducted before we will be able to make highly reliable assessments of future change.

Our model validation experiments suggest that we can make several strong inferences regarding future climate and vegetation change in eastern North America. Given a doubling of atmospheric CO_2 concentrations, it appears likely that large-scale climatic warming will characterize the next couple of centuries. This warming will probably occur in all seasons. Significant changes in precipitation will also probably occur, but intermodel differences suggest that we must remain less certain about the geographic and seasonal patterns of future precipitation changes. Our results suggest that temperature change alone could result in significant vegetation change across eastern North America, and that even the most modest simulated temperature change for eastern North America could induce significant vegetation change. Precipitation change, particularly where it tends toward greater aridity, is likely to increase the magnitude of future vegetation change.

Response surfaces and forest stand modeling suggest that plant taxa will respond individualistically to trace-gas-induced climatic change. Vegetation models that cannot accommodate the the response of individual taxa are therefore of limited utility. The most dominant and likely pattern of future change will be large-scale northward shifts in plant populations. Our model validation experiments indicate that our projected range-boundary movements are more reliable than our assessments of future taxon abundance gradients. In any case, both taxon range-boundary and abundance change could be large over the next two centuries. Our use of two independent vegetation models coupled with three independent $2xCO_2$ climate scenarios reinforces these conclusions. These model experiments also suggest that significant systematic changes in total forest biomass and longitudinal shifts in plant populations could occur.

The eastward extension of prairie-forbs simulated in our $2xCO_2$ response-surface experiment coincides with a biomass decline south of the Great Lakes in our forest stand simulation results. Forests in this region might become more open or savannalike. Both models suggest that the composition of the mixed conifer-hardwood forests across the Great Lakes and New England regions could experience dramatic change, particularly with the significant replacement of pine populations by oak populations. Spruce-rich forests of the northeast U.S. could be in danger of serious decline. Both vegetation models suggest that southern pine populations could extend northward as climate warms. Populations of most other tree taxa are likely to be affected by trace-gas-induced climate change. The results of our model validation experiments lend confidence to the foregoing $2xCO_2$ assessment. Caution is advised, however, against taking our results without consideration of the uncertainties discussed below, and particularly against interpreting our results at a scale finer than about 10^5 km^2. We are relatively secure in projecting that major vegetation change could occur over the next two centuries, but have little basis for speculating on the exact pattern of change in any given county or township.

UNCERTAINTIES AND THE NEED FOR FUTURE WORK

One uncertainty in our work is the lack of information on the transient response of the vegetation to future climatic change. Our results portray the equilibrium response of the vegetation to climatic change and how vegetation patterns in eastern North America might look when vegetation change has fully caught up with the unprecedented fast climatic change that might occur in the future. Empirical data on important factors are lacking. We do not know how fast plant populations can track changing climate. Although evidence of significant disequilibrium between plants and climate is lacking in the record of the past 18,000 years, it is possible that rates of seed dispersal and soil development could limit the rates of future vegetation change. The inability of species to migrate to sites newly favored by climatic change could increase the likelihood of significant biomass declines in some areas (Solomon et al., 1984; Solomon, 1986; Solomon and West, 1987). Our results highlight some of the plant taxa that might be sensitive to future climatic change and where they will be sensitive. The results of Botkin et al. (this volume) support ours, and indicate that significant changes in the vegetation of eastern North America might take place as early as the year 2010.

Our response surface modeling used mean January temperature, mean July temperature, and mean annual precipitation as predictor variables. These variables are correlated with other climate variables in eastern North America and serve to represent the influence of winter stress, growing season warmth, and water stress on plants. Future work must consider the effects of other variables, including climatic variance (Solomon and West, 1985; Neilson, 1986). Our stand-simulation experiments included the influence of monthly climate data, and supported the results of our response surface modeling.

The conclusion that future climate-induced vegetation change could be large is supported by the broad-scale agreement among results generated using two independent vegetation models and three independent climate models. More importantly, our ability to simulate aspects of future vegetation is reinforced by our ability to simulate past vegetation. The crucial role of model validation is further highlighted, however, by the partial lack of fit between simulated and observed pollen maps. Although it is valid to test the sensitivity of a specific local region or site to hypothesized climatic forcing, our results clearly show that local-scale predictions are not yet possible.

Our validation experiments reveal that we can only model certain aspects of vegetation with confidence. The forest stand model simulates the establishment, growth, interaction, and death of 72 tree species, but our results suggest that not all of these species are simulated in a realistic manner. This result supports earlier work with forest stand models (Solomon et al., 1980; Solomon and Shugart, 1984). Part of the problem undoubtedly lies in the fact that our vegetation modeling did not include the influences of all climatic variables, simulated climatic variance, realistic soil processes, forest disturbance, and other important processes (Solomon and West, 1985; Davis and Botkin, 1985; Solomon, 1986; Pastor and Post, 1986). The subtropical tree species of Florida were also omitted from the model. These additional influences must be considered in the next generation of vegetation models, and the ability of these models must be tested using paleoclimate and paleovegetation data. Our modeling results clearly demonstrate, however, that the current generation of simple models can yield useful broad-scale assessments of vegetation change.

The experimental design of our model validation framework is also just a beginning. The high degree of fit between simulated and observed vegetation after 9,000-year B.P. argues that much of the mismatch for earlier periods is due to poor specification of climatic boundary conditions. Paleoclimatic research is needed to reduce this uncertainty. GCM improvement must include (1) systematic programs to compare the results of different GCMs and (2) validation of paleoclimatic simulations against the observed paleoclimate and paleovegetation record. We also need more paleovegetation data, particularly for the period prior to 10,000-year B.P. We have begun to work on response surfaces for Continuous Forest Inventory (Olson et al., 1980; Delcourt et al., 1984) and species range (Little, 1971) data. The use of range data will allow us to extend our empirical climate-vegetation modeling to all species for which we have range data. These models can be tested but will require the collection and compilation of plant macrofossil data. The full power of paleovegetation data for testing models was only touched upon in this report.

One major uncertainty regarding future vegetation change is the rate at which this change will occur. Our results only illustrate how large this change could be over the next 100-200 years and the direction that this change will probably follow. Even though we have models capable of simulating time-dependent change (e.g., the stand-model), we are limited in our ability to judge their accuracy. The same holds true for vegetation models that simulate the direct effects of rising trace-gas concentrations (e.g., CO_2 "fertilization") on plants. At this time, there are not even enough data to access the potential impact of these direct effects on natural forests (Strain, 1985; Solomon, 1986). Careful paleoclimatological and paleoecological research could eventually provide a means for testing the ability of models to simulate time-dependent vegetation change.

CHAPTER 6

CONCLUSIONS

The results presented in this report suggest that state-of-the-art climate and vegetation models can be used to assess broad-scale patterns of past and therefore future vegetation change. Plant taxa will respond individualistically to trace-gas-induced climate change and these responses could be significant across eastern North America. We have demonstrated how paleoclimatic and paleoecological data can be used to identify model uncertainties. Our results highlight the need for further ecological, paleoecological, paleoclimatological, and modeling research. All future assessments of potential trace-gas-induced climate and vegetation change should include provisions for model validation.

ABBREVIATIONS

CCM	Community Climate Model (NCAR)
GCM	General Circulation Model
GISS	Goddard Institute for Space Studies
NCAR	National Center for Atmospheric Research
OSU	Oregon State University
year B.P.	years Before Present

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EFFECTS OF CLIMATE CHANGE ON FORESTS OF THE GREAT LAKE STATES

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FINDINGS[1]

There is widespread concern over the climate change that may be induced by increases in the carbon dioxide concentration in the atmosphere, but there have been few ways to assess the impact of such changes on natural ecosystems. Recently developed global climatic models project that mid-latitudes would experience pronounced warming and drying out of soils, which suggests that there might be major changes in mid-latitude forests. But the kind and degree of such changes in vegetation have not been subject to quantitative evaluation. One of the few methods available for such an evaluation is computer simulation. Fortunately there is a well-established model of forest growth which has been shown to be realistic and has been used to study the response of forests to long-term climatic change. We report the application of this model to evaluate effects on forests of the Great Lake States to changes in temperature and rainfall induced by changes in the CO_2 concentration of the atmosphere.

Two representative sites were considered, one in the southern and one in the northern portions of the Great Lake States. In the southern part, weather records from Mt. Pleasant, MI, were chosen to represent a heavily settled area where commercial forests are still an important economic resource. Forests in this area are transitional between northern hardwoods and oak-dominated forests. In the northern portion, weather records from Virginia, MN, were chosen to represent heavily forested areas in and near the Superior National Forest (where commercial forestry has been important) and the Boundary Waters Canoe Area (BWCA), a nationally designated wilderness area (important for recreation and biological conservation).

The climate change is projected to lead to major changes in the forest composition, that is, in the species of trees which dominate the forests, as illustrated in Figure 1 and Figure 2. In the north, boreal forests may be replaced during the next 90 years by northern hardwood forests, now characteristic of areas to the south. Effects depend on soil type and soil water conditions. In the Boundary Waters Canoe Area, areas where balsam fir dominates and upland areas where white birch or quaking aspen are now dominant may be converted to forests dominated by sugar maple; white cedar bogs may be converted to treeless bogs (Figure 1).

In the south, hardwood forests that are transitional between sugar maple-dominated hardwoods and oak forests may be converted to oak woodlands or savannahs, which occur to the south under current conditions, or even to treeless prairies, which occur much farther to the west (Figure 2).

Wood production and the accumulation of total biomass may be greatly affected, but the effect depends heavily on soil and soil water conditions. Forests on dry sandy soils in the southwestern part of the region may be converted to prairie and savannah in which no significant wood production takes place. Soils with abundant soil water may continue to support trees but with a somewhat lower wood production and biomass.

In the north, cedar bog land may be converted to a treeless bog, while upland areas, in contrast, may undergo an increase in wood production and biomass accumulation where saturated soils are made somewhat drier and better as sites for tree growth.

The climate change would have major effects on the forest industry in the Great Lake States. This industry is currently adapted for a certain complement of species, primarily for softwoods used in the production of paper pulp and construction materials. The species that would become most economically important under

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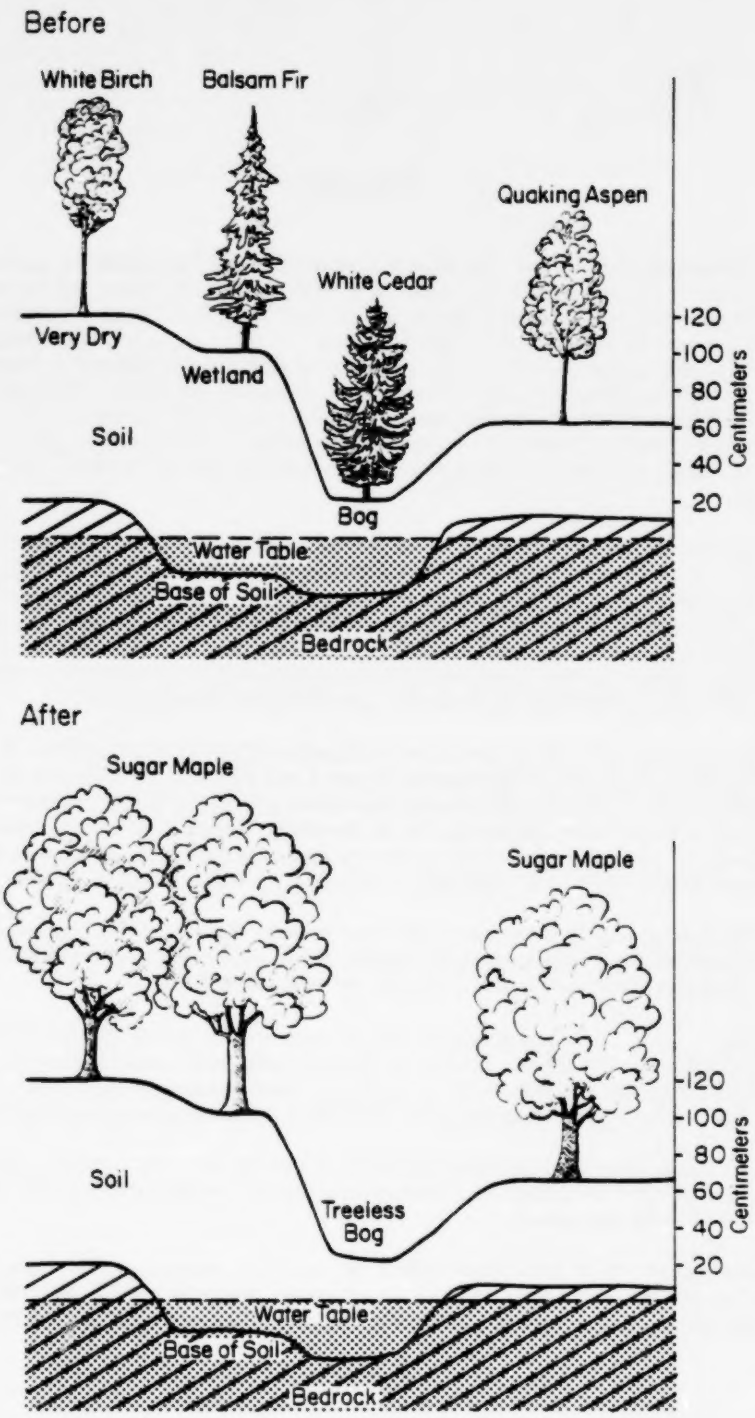
Before
White Birch
Balsam Fir
Quaking Aspen
White Cedar
Very Dry
Wetland
Soil
Bog
Water Table
Base of Soil
Bedrock
120
100
80
60
40
20
Centimeters
After
Sugar Maple
Sugar Maple
Soil
Treeless Bog
Water Table
Base of Soil
Bedrock
120
100
80
60
40
20
Centimeters

Figure 1. Diagram of predicted change in forests of northern Minnesota beginning with the current climate in 1980 ("Before" in the diagram) and ending after undergoing the climatic change as projected by the GISS model transient A, 90 years later in 2070 ("After" in the diagram).

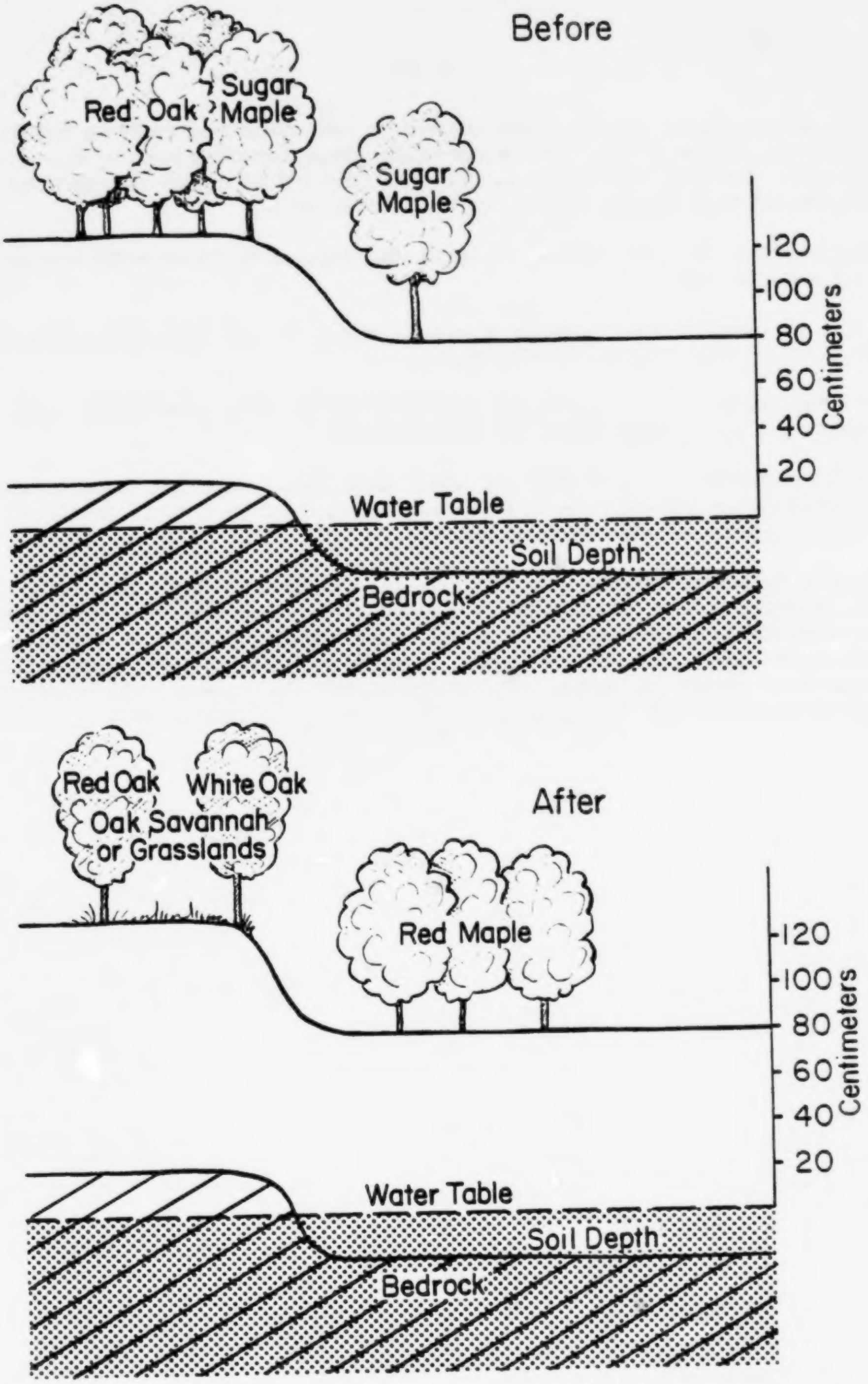
Before
Red Oak
Sugar Maple
Sugar Maple
120
100
80
60
40
20
Centimeters
Water Table
Soil Depth
Bedrock
Red Oak
White Oak
Oak Savannah or Grasslands
After
Red Maple
120
100
80
60
40
20
Centimeters
Water Table
Soil Depth
Bedrock

Figure 2. Diagram of predicted change in forests of southern Michigan beginning with the current climate in 1980 ("Before" in the diagram) and ending after undergoing the climatic change as projected by the GISS model transient A, 90 years later in 2070 ("After" in the diagram).

twice CO_2 steady-state climate would be hardwoods such as oaks and maples, useful for furniture and other decorative purposes, which would have much longer rotation times (harvesting could be done less frequently) than the softwoods. Thus there would be a major shift in the character of the forest industry whose costs should be evaluated; the shift would require different equipment and markets.

Results from tests run to date suggest that significant changes in the forests could occur as early as the year 2010 and as late as 2040.

The time and funds available for this study placed a limit on the work that could be done, and it would be advisable to extend the work in the following ways:

(1) test the sensitivity of the results to the value of parameters in the forest growth model, such as the maximum longevity of trees and the temperature limits of growth;

(2) test the sensitivity of the results to certain aspects of the climatic projections, including the combination of weather records used as a basis for the simulation, and the calculation method to determine the ratios used to modify control climate to simulate modified climates;

(3) consider the interaction between the climatic effects considered here and other environmental factors including fire, pathogens, insects, air pollution, UV-B radiation fluxes, acid rain and gaseous oxidants, human management and human-induced disturbances, as well as the frequency, intensity, and duration of extreme weather events including wind, flooding, and drought. In particular, it is especially important to determine how sensitive the projected timing of changes in forest composition under the transient climatic regimes is to specific values of parameters in the forest models and to key assumptions in the climate models.

CHAPTER 1

INTRODUCTION: BASIC ISSUES

Growing concerns with the possibility of a major climatic change due to the increase in carbon dioxide in the atmosphere as a result of human activities have led to a need to predict the possible effects of such a climate change. An important issue is the response of forests and woodlands to such a change. Forests and woodlands are important not only as commercial crops for lumber, and pulp, but also in urban areas as recreational urban parks, in rural areas for multiple uses including: soil conservation and erosion control; water supply; habitat for wildlife; maintenance of streams in a form and shape that can support populations of fish; as recreation for camping, fishing, hunting, nature viewing; for aesthetic values; and for conservation of biological diversity. Woodlands containing endangered species and forests designated as wilderness preserves are of special legal concern. Finally, forests play an important role at a global level in terms of chemical cycling throughout the biosphere and in climate dynamics. Forest trees and soils together are estimated to store more carbon than is found in the atmosphere (Woodwell et al., 1977). Under support from EPA, we have begun to investigate the effects of global warming on the forests of the Great Lake States. The results of the work are reported here.

CHAPTER 2

METHODOLOGY

The TIMBER! forest model ((C) 1983, 1988 by D.B.Botkin and T.E. Reynales), based on the JABOWA forest model developed by D.B. Botkin, J. Janak, and J. Wallis (1972),[2] was used to investigate the possible effects of climate change on forests of the Great Lake States.

Projected climatic changes made use of the following global climate dynamics models, whose output was modified especially for these studies by Dr. R. Jenne of NCAR: GISS "normal" climate; GISS "twice CO_2" climate; GISS Transient A and Transient B; GFDL "twice CO_2" climate; and the OSU "twice CO_2" climate. The outputs from these models were used to modify real weather records, which were obtained in computer form for stations in the Great Lake States.[3] Note that this report concerns the response of forests to climate change induced by of an increase in CO_2 concentration; direct physiological effects of atmospheric CO_2 increase on tree growth is not simulated.

THE FOREST MODEL

In 1972 Botkin, Janak, and Wallis first reported the development of a computer model of forest growth (Botkin et al., 1972), which has since been shown accurate and realistic and has been applied to forests around the world (West et al., 1981; Prentice, 1986). Other forest models that are now often referred to as "gap-phase" models are derived from and essentially identical to earlier versions of JABOWA. For example and for purposes of comparison for the EPA study, the model discussed by Shugart (1984) is derived from our model and to the best of our knowledge contains most of the algorithms from the version of JABOWA in Botkin et al. (1972). One of these derivative models has been used to investigate some aspects of CO_2- induced climate change (Solomon and West, 1983), but these use climate projections from Mitchell (1983). The TIMBER! model incorporates a number of advances including (a) a more complete method of handling the relationships between water and tree growth, making possible a separation of floodplain communities from bog and other wetland communities;[4] (b) relationship between nitrogen concentration in the soil in terms of and tree growth;[5] and (c) provides a more realistic treatment of growth and reproductive rates among species. TIMBER! also incorporates 40 species of trees, which are the major native trees found in the northern hardwoods and boreal forests of eastern and mid-western North America and all of the tree species found north of Connecticut since the end of the last major period of glaciation. (A few minor species that are never dominant in the Great Lake States are not included, such as boxelder and bur oak.)[6]

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[2] Botkin, D.B., J.F. Janak and J.R. Wallis. 1973. Some ecological consequences of a computer model of forest growth. J. Ecology 60: 849 - 872.

[3] The weather records were provided in computer format by R. Jenne of NCAR.

[4] This follows methods developed by Botkin, D.B., and R.E. Levitan. 1977. Wolves, moose, and trees: an age specific trophic-level model of Isle Royale National Park. IBM Research Report in Life-Sciences RC 6834, 64 pp.

[5] This follows methods reported in Aber, J.S., D.B. Botkin and J.M. Melillo. 1978. Predicting the effects of different harvesting regimes on forest floor dynamics in northern hardwoods. Canad. J. Forest Research 8: 306 - 315.

JABOWA-type models have been used to simulate forest growth in many parts of the world (Shugart, 1988), and for many purposes. The JABOWA model has been applied to consideration of the effects of acid rain on forest growth (Aber et al., 1978; Aber et al., 1979). A version of TIMBER! was used to investigate the effects of climate change since the end of the last ice age on forests of New England (Davis and Botkin, 1985).

Pertinent to this EPA study, one of our earliest applications of JABOWA was to simulate the effects of CO_2 fertilization of forests resulting from the atmospheric increase of CO_2 due to the burning of fossil fuels and decrease in forest and soil organic matter (Botkin et al., 1973).

JABOWA-type models simulate growth of individual trees on small plots; trees compete for light, water, and soil nutrients;[7] their growth is affected by environmental conditions including mean monthly temperature and precipitation, soil depth, characteristic soil particle size, and soil fertility. An assumption of the model is that each plot is small enough so that a large tree shades every other tree on the plot. Each year the growth and mortality of individual trees and reproduction of species are determined based on competitive and environmental conditions. Aspects of the model are stochastic, so that the model can be used to consider variability within a forest and to generate statistical means, variances, and confidence intervals. The model has been well documented and verified elsewhere (Botkin et al., 1972, 1973; Davis and Botkin, 1985).

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[6] The species considered in this model are sugar maple (Acer saccharum); yellow birch (Betula allegheniensis); white ash (Fraxinus americana); mountain maple (Acer spicatum); striped maple (Acer pensylvanicum); pin cherry (Prunus pensylvanica); choke cherry (Prunus virginia); balsam fir (Abies balsamea); white birch (Betula papyrifera); mountain ash (Sorbus americana; red maple (Acer rubrum); scarlet oak (Quercus coccinea); hornbeam (Carpinus spp.); green alder (Alnus crispa); speckled alder (Alnus rugosa); black ash (Fraxinus nigra); butternut (Juglans cinerea);white spruce (Picea glauca); black spruce (Picea mariana); jack pine (Pinus banksiana); red pine (Pinus resinosa); white pine (Pinus strobus); trembling aspen (Populus tremuloides); white oak (Quercus alba); northern red oak (Quercus rubra); white cedar (Thuja occidentalis); hemlock (Tsuga canadensis); silver maple (Acer saccharinum); tamarack (Larix laricina); basswood (Tilia americana); bigtooth aspen (Populus grandidentata); balsam poplar (Populus balsamifera); black cherry (Prunus serotina); eastern red cedar (Juniperus virginiana).

[7] The first modification of the JABOWA model to allow consideration of soil nutrients in an explicit formulation were reported in Aber, J.S., D.B. Botkin and J.M. Melillo. 1978. Predicting the effects of different harvesting regimes on forest floor dynamics in northern hardwoods. Canad. J. Forest Research 8: 306 - 315; and Aber, J.D., D.B. Botkin and J.M. Melillo. 1979. Predicting the effects of different harvesting regimes on productivity and yield in northern hardwoods. Canadian J. Forest Research 9: 10 - 14.)

CHAPTER 3

CHOICE OF WEATHER STATIONS AND LOCATIONS

Two weather stations were selected for the studies reported here: Mt. Pleasant, MI, and Virginia, MN. At each station 30-year records (1951-1980) were used. It is important to understand that the results reported here represent the responses of forests in the general area of each station and not only forests exactly at those stations. This is because the output from the climate dynamic models is for large areas and because the forest model described above can consider a wide variety of forests in many different habitats, with different soils and water relations.

Mt. Pleasant was chosen to represent the impact of climatic change on woodlands in settled areas, on hardwood forests of commercial use, and on woodlands useful for other multiple use purposes. In addition, our results indirectly provide insights into the possible response of certain fruit trees. Mt. Pleasant lies in the southern portion of the Great Lake States, in a region which was forested in presettlement times by northern hardwoods forests (forests typically dominated by sugar maple on good, well-drained soils), but near to a transition to oak forests to the south. Today this area is heavily settled.

Virginia, MN, as chosen to represent the impact of climatic change on forest growth in on coniferous woodlands of commercial use and on a wilderness area. Forests in this area are of commercial value for pulp, paper, and construction. In addition, Virginia is near the Superior National Forest, managed for multiple uses including timber sales, and it is near the Boundary Waters Canoe Area, one million acres of federally designated protected wilderness important for recreation and biological conservation. The Boundary Waters Canoe Area is especially useful because its history since the end of the last ice age has been reconstructed (Heinselman, 1970), the frequency of natural forest fires is well known (Heinselman, 1973), and the distributions and abundances of major tree species are comparatively well understood. In addition, we have done extensive field work in portions of this area (Botkin et al., 1984; Hall et al., 1989 in press). Virginia, MN, lies in the northern part of the Great Lake States in the transition between northern hardwoods forests and the boreal forests (typically dominated by spruce and fir, with aspen, white birch, and pines common in younger forests and drier sites).

CREATION OF EXPERIMENTAL WEATHER RECORDS

Weather records were prepared for control (normal) conditions and treatment conditions using theoretical output from climatic dynamic models to modify existing weather records. The assumption implicit in creation of treatment conditions was that the yearly and seasonal variation of treatment climates was adequately simulated by the variation observed in the actual weather record. This assumption may be in error since the period of the Little Ice Age between the late 1400's and the mid 1800's was characterized by greater than usual variation in temperature and precipitation (Bryson and Murray, 1977).

During control runs (normal CO_2) the TIMBER! model used the actual 30-year weather record, with the record repeated for simulations of more than 30 years. To model forest growth in the Boundary Waters Canoe Area where there are no weather stations, the Virginia, MN, weather records were modified slightly to represent an area to the north as we have done previously for other sites (Botkin et al., 1972). In this case it was assumed that the area to the north would experience weather equivalent to increasing the elevation above Virginia and using standard temperature and precipitation lapse rates; this method has been used by us previously.

The model is stochastic, allowing consideration of the variations to be expected in a forest. Multiple experiments with identical initial conditions and weather patterns over time can be used to project mean, standard errors, and confidence intervals. In the work reported here, 60 replicates were obtained for each trial. Each replicate began with 1951 data and followed the same weather sequence.

In each treatment, projected weather records were prepared as follows: the ratios between the model "normal" steady-state output and the CO_2-enhanced climate were calculated by R. Jenne and provided to us in computer format. Ratios were calculated for mean monthly temperature and mean monthly rainfall. The actual mean monthly temperature and precipitation were then multiplied by the appropriate ratios to generate "treatment" climates. It must be emphasized that the model results represent projections of forest response based on the climate projection input to the model. We do not assume that the model projections will actually occur, but rather, the projections represent various scenarios that might occur if any of the climate simulations occur. The various climate models represent the state-of-the-art in climate simulation; greater certainty associated with projected forest responses can be expected as the climate models improve.

The "normal" output from a climate model represents steady-state conditions assuming that the present concentration of carbon dioxide is maintained. "Twice CO_2" represents a steady-state condition in which carbon dioxide is twice current concentrations in the atmosphere. "Transients" provide a simulation of weather in a transition from the model projections of climate under current CO_2 concentrations to future climatic conditions. These results were used to generate ratios of change for real weather records.

EXPERIMENTS

The following experiments are reported: the growth of forests from a clearing were compared for (1) 1951-1980 climate; (2) GISS steady-state; (3) GFDL steady-state; (4) OSU Steady-state; (5) GISS transient A; and (C) GISS transient B. Each experiment was replicated 60 times and the results were averaged and the 95% confidence intervals were calculated. The southern portion of the Great Lake States was represented by Mt. Pleasant weather records, and for these weather records growth of forests from clearings was considered. The northern portion of the Great Lake States was represented by Virginia, MN. weather records, modified to represent the Boundary Waters Canoe Area and nearby Superior National Forest; for these, growth both from clearings and of old age (400-year) forest stands was considered. Four soil types were used:

1) deep comparatively dry soils;

soil depth - 1.0 meters
depth to water table - 1.2 meters

White birch - 3378 ± 56 $cm^2/100m^2$ basal area
- 12.6 ± 0.2 $stems/100m^2$

Yellow birch - 93 ± 29 $cm^2/100m^2$ basal area
- 1.9 ± 0.6 $stems/100m^2$

White spruce - 91 ± 1.3 $cm^2/100m^2$ basal area
- 4.9 ± 0.01 $stems/100m^2$

2) deep comparatively wet soils;

soil depth - 1.0 meters
depth to water table - 0.8 meters

Balsam fir - 2768 ± 53 $cm^2/100m^2$ basal area
- 8.2 ± 0.15 $stems/100m^2$

Sugar maple - 224 ± 1.2 $cm^2/100m^2$ basal area
- 4.0 ± 0.05 $stems/100m^2$

3) shallow wetland soils;

soil depth - 0.5 meters
depth to water table - 0.2 meters

White cedar - 2693 ± 93 cm^2/100m^2 basal area
- 1.0 ± 0.03 stems/100m^2

4) shallow dry upland soils;

soil depth - 0.5 meters
depth to water table - 0.6 meters

Trembling aspen - 2078 ± 72 cm^2/100m^2 basal area
- 1.0 ± 0.03 stems/100m^2

Balsam fir - 113 ± 1 cm^2/100m^2 basal area
- 2.3 ± 0.13 stems/100m^2

Sugar maple - 278 ± 1 cm^2/100m^2 basal area
- 1.0 ± 0.01 stems/100m^2

These soil types support a broad range of forest conditions from old age cedar bogs and old age balsam fir stands to regrowth of aspen on thin sandy soils. Using the monthly temperature and precipitation estimates, the model generates moisture conditions using a modified Thornthwaite water balance method (Thornthwaite, 1948; Sellers, 1965) as described in Botkin et al. (1973).

Note that the transients involve projections from the present into the 21st century, while the steady-state experiments represent conditions under which the CO_2 concentrations were to remain constant at twice the present atmospheric concentrations, a condition that is not expected to occur (the CO_2 concentration will continue to vary further into the future). The steady-state expectations are of interest, however, to compare expected growth under current conditions with the effects of a doubling in CO_2. Under each set of weather conditions, trials were conducted for two major soil types: deep comparatively dry soils and deep relatively wet soils.[8] These two soil conditions represent generally good sites for forest growth under current climatic conditions; most soils would be shallower than these and therefore have less water available for tree growth or else, in wetland situations, be more saturated with water and subject tree roots to stress because of lack of oxygen. These relatively good conditions were chosen on purpose to weight the results toward the more optimistic side. The soil particle size chosen is on the sandy side, which is common in the Great Lake States. A soil with a finer average particle size (a loam soil) would be somewhat more fertile and would have a better water holding capacity. Clay soils tend to lead to saturated conditions, leading to a decline in forest growth under the normal climatic regimes used in this work. The fertility of the soil used in the experiments is high, but could be made even higher; however, to our knowledge, it represents a quite fertile natural soil of the region.

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[8] In the parts of Michigan and Minnesota considered in these simulations, the following species do not occur: grey birch, eastern red cedar, red spruce, pitch pine, and (for Minnesota) beech; blights on American elm and chestnut will exclude these as well; therefore, seed sources would not be available. These species were therefore excluded from the simulation experiments described here; 33 species could enter any plot if the site conditions were appropriate.

CHAPTER 4

RESULTS

Climatic Changes

The climate change is strong. Projected steady-state alterations of the climate for one year are shown in Figure 3. The GISS, GFDL, and OSU doubled CO_2 outputs convert Mt. Pleasant records from winters that commonly have months with mean temperatures below freezing to series of years with winters in which no month has an average temperature below freezing. The GISS and GFDL models increase January temperatures approximately 10°F, whereas the mean January temperature never exceeded the mid 20s (°F). From 1950 to 1980, the projected range for Mt. Pleasant January temperature ranged from the high 30s (°F) to the mid 20s (°F). In other words the 1951-1980 maximum January mean value becomes the minimum value in the projected climatic warming. The OSU model projects January means that are only slightly colder.

Similar increases occur for the July mean temperature. For the GISS model, average temperatures range from the mid 70s (°F) to above 80°F, in contrast to the 1951-1980 range from the high 60s (°F) to the mid 70s (°F). These changes in temperature and rainfall would have great effects on forests and other vegetation. Such summer increases would greatly increase evaporation of water from soils and trees, and lead to a much drier climate. The effects on rainfall are much less pronounced, with a slight decrease in rainfall in some years.

The GFDL gives considerably more severe projections for summer temperatures, with July means exceeding 90°F and never descending below 82°F. The OSU model projects somewhat cooler July mean temperatures than the two other models, with most values remaining in the low to mid 70s (°F).

The GISS model transient A increasingly deviates from the actual climate so that July mean temperatures show a definite increase after the first decade (Figure 4A). Transient B, which has projections for only 60 years, shows increases on the order of several degrees Fahrenheit by the fifth decade (Figure 4B). Such summer increases would greatly increase evaporation of water from soils and trees, and lead to a much drier climate. The effects on rainfall are much less pronounced, with a slight decrease in some years.

Projected effects are given for three models, GISS, GFDL, and OSU. Values are the average monthly temperature for the year 1951 for the actual weather record ("Normal"), and for this temperature record as modified by the steady-state twice CO_2 climate for each of three climate models. The altered temperature was calculated by multiplying the actual mean monthly temperate by the ratio of the treated to normal steady-state climates for each model.

Natural Forests: The Boundary Waters Canoe Area

The transient climatic regimes lead to surprisingly rapid changes which are very sensitive to soil moisture conditions; using the Giss transient-A climate beginning with 1980 conditions, the model predicts that a significant change in forest composition would occur in the Boundary Waters Canoe Area by year 2010 and transient B by year 2040. By 2010 under transient-A conditions, a 400 year-old stand dominated by balsam fir on deep, fertile, moist soil (Figure 5) would decline to one-third of the balsam fir basal area under the 1951-1980 weather regime. Sugar maple replaces fir as the dominant species, and the total biomass nearly triples. In a wetland, a 400 year-old white cedar forest with a total basal area of 2685 $cm^2/100m^2$ declines to a nearly treeless bog with total basal area of only 134 $cm^2/100m^2$ (Figure 6). On a deep, drier but fertile sandy upland soil the white birch dominant declines to about 10 percent of its starting level in about 40 years, and is replaced by a sugar maple forest (Figure 7), with a decline in total biomass accumulation to 16 kg/m^2, about half the biomass of 28 kg/m^2 under normal conditions after 90 years (Figure 8). These dramatic effects of the transient-A climate change also suggest that we should be able to find and document some boreal forests that are currently changing to sugar maple forests.

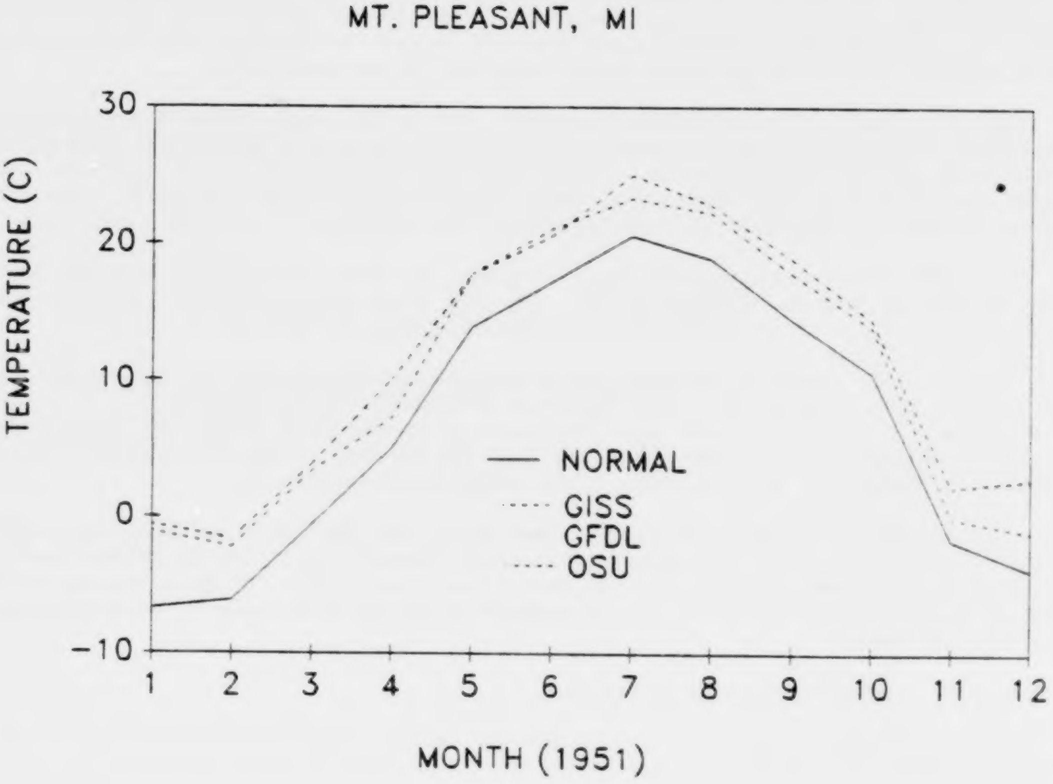


Figure 3. The projected effects of a doubling of the CO_2 concentration in the atmosphere on temperature for Mt. Pleasant, MI. Projected effects are given for three models, GISS, GFDL, and OSU. Values are the average monthly temperature for the year 1951 for the actual weather record ("Normal"), and for this temperature record as modified by the steady-state twice CO_2 climate for each of three climate models. The altered temperature was calculated by multiplying the actual mean monthly temperature by the ratio of the treated to normal steady-state climates for each model.

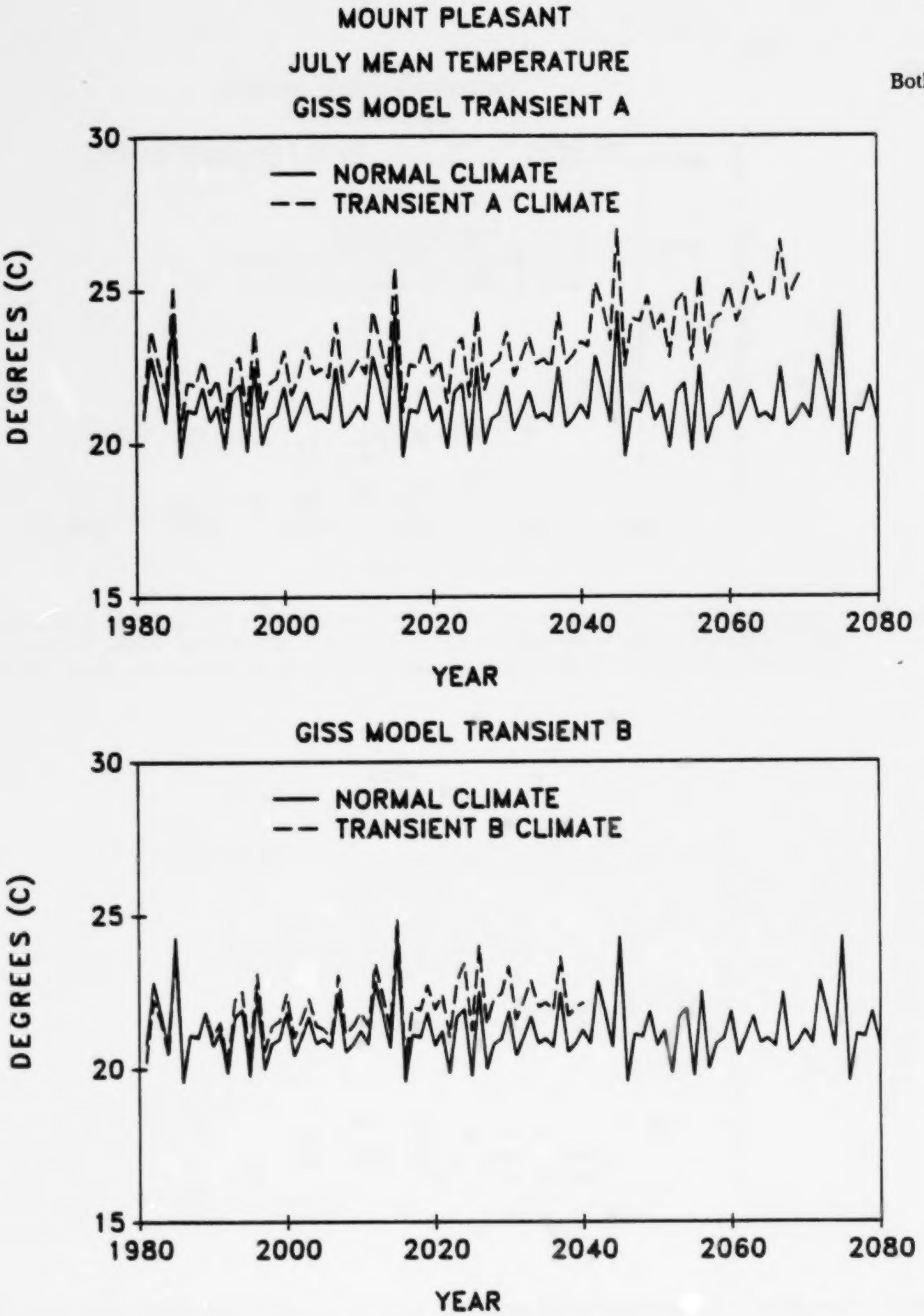


Figure 4. Temperature change during the next decades. These temperature changes are for the July mean temperature for Mt. Pleasant, MI ("Normal") and as modified by the GISS climatic model transient A and transient B.

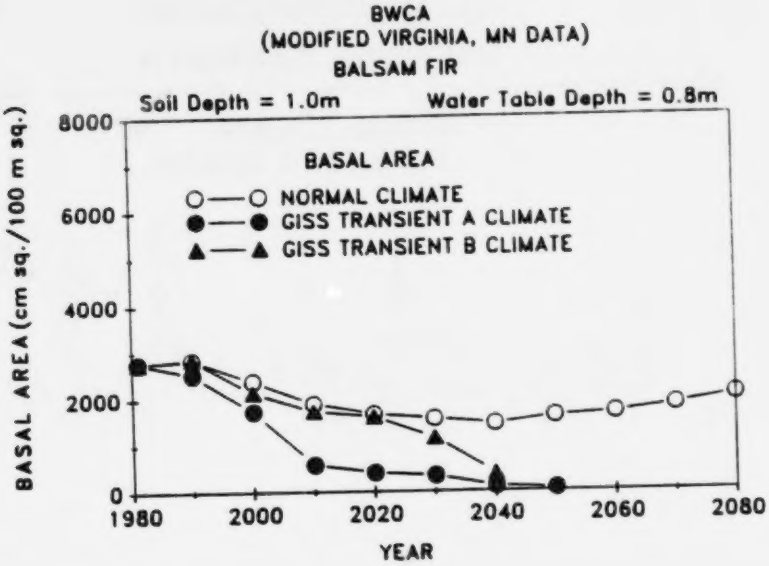


Figure 5. Changes in forest composition during the next century for a deep, wet sandy soil in the boundary waters canoe area. The projections shown here are for a 400-year-old balsam fir stand that is characteristic of northern Minnesota and throughout the northern portion of the Great Lake States.

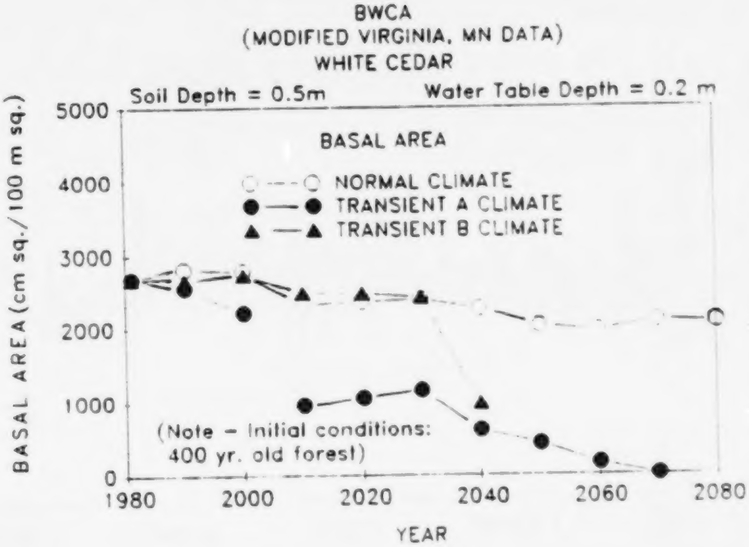


Figure 6. Changes in forest composition during the next century for a cedar bog in the boundary waters canoe area. The projections shown here are for a 400-year-old white cedar bog which is characteristic of certain water-saturated soils in northern Minnesota and throughout the northern portion of the Great Lake States.

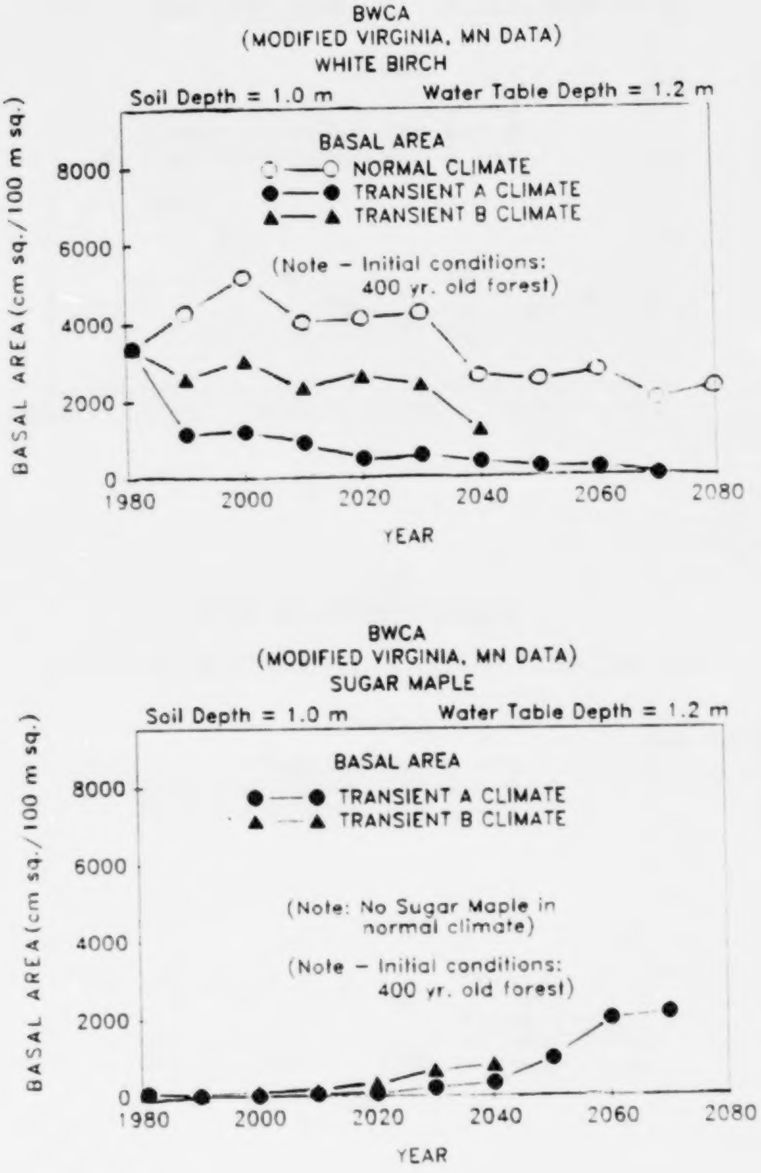
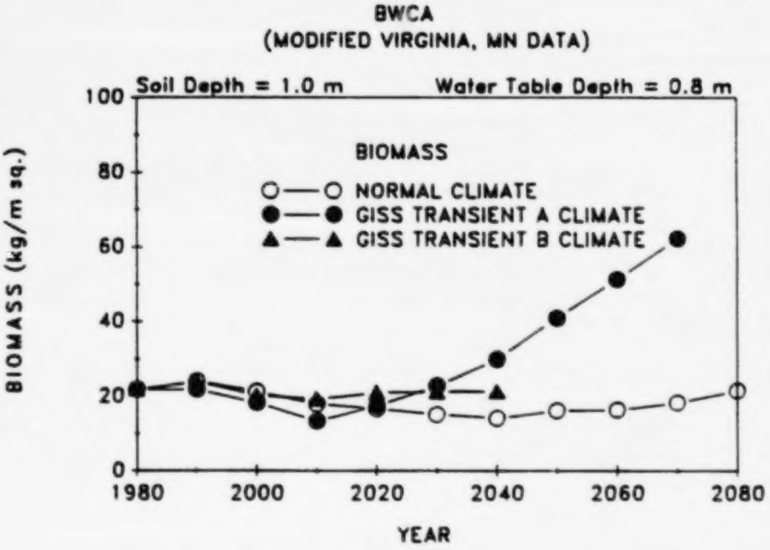


Figure 7. Changes in forest composition during the next century for a deep, dry sandy soil in the boundary waters canoe area. The projections shown here are for a 400-year-old forest on a deep, dry sandy soil which, in this case, is dominated by white birch in 1980. Such stands are typical in northern Minnesota and throughout the northern portion of the Great Lake States.

(A)



(B)

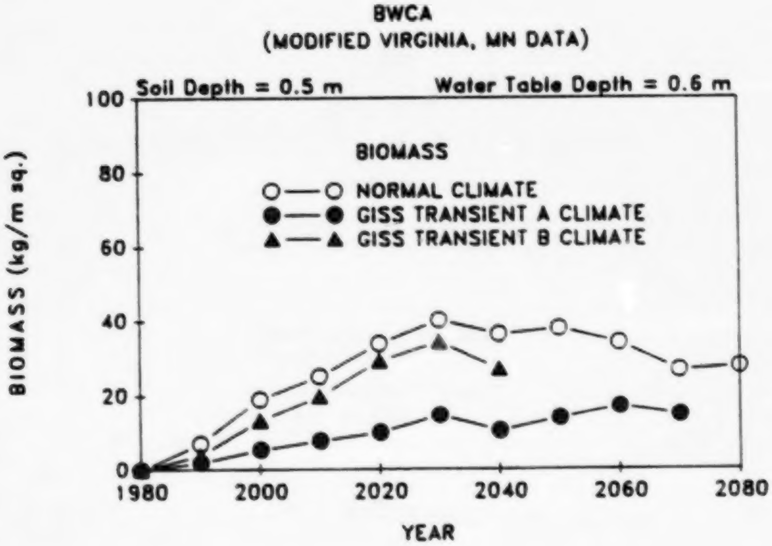


Figure 8. Changes in biomass for (A) the balsam fir stand shown in Figure 5, and (B) a clearout stand on a thinner, drier soil representative of the boundary waters canoe area and northern Minnesota.

While the three climate models differ considerably in their projections, all projected twice CO_2 steady-state climates lead to major changes in vegetation. In the BWCA, natural fire frequency has been once a century (Heinselman, 1970) and early successional stands are common on the landscape;[9] thus consideration of growth from clearings is important. On deep, relatively moist soil, wetlands that now develop into larch-dominated bogs regrow to red maple-dominated wetlands characteristic of warmer areas. Thus both old-age and regrowth forests change from boreal to northern hardwoods.

These conclusions appear to contradict those proposed by some workers (Wigley et al., 1980), who have suggested that an increase in CO_2 concentration would augment tree growth because increases in the CO_2 concentration in area above a potted plant in a greenhouse lead to great increase in seedling growth. This consideration alone has led some scientists to believe that changes in forest composition during the next 25 to 30 years were expected to be only barely measurable. However, greenhouse and controlled-environment experiments usually fail to consider the considerable effect of CO_2-induced climate change on site conditions that is projected by our work.[10] CO^2 fertilization may indeed increase growth of greenhouse plants, but these results are difficult to extend to the natural environment, where many factors operate to control plant growth.

As a consequence of these major changes in vegetation, large alterations would occur in the forest ecosystems; chemical cycling, storage of organic matter, and rates of decomposition differ between conifer-dominated boreal forests and the northern hardwood forests. The flux of chemical elements from forests to streams could change. The habitat for wildlife would be altered, and one would expect the dominant species of wildlife to change with the vegetation. For example, areas suitable today to moose would become favorable to white-tailed deer. The entire character of the BWCA as a wilderness area would be altered.

The response of the forests is very sensitive to soil conditions. This is because the climatic changes lead to a great increase in evapotranspiration; although rainfall increases, the evaporative losses increase more and water becomes limiting. This explains why upland sites can be converted to savannahs while wetlands can maintain substantial, if reduced, forest growth of species presently dominant further south.

IMPACTS OF CLIMATIC CHANGE

Southern Region of the Great Lake States

Transition from Current Conditions

Under the 1951-1980 actual climate, following a simulated clearing in 1980, a normal forest develops in which red oak, sugar maple, white oak, and white pine are dominants on drier sites (Figure 9), and sugar maple, red maple, white ash, and basswood are dominants on wetter sites (Figure 10) throughout the first 100 years' growth. In transient A climate, which contains projections for 90 years, sugar maple does not occur on the drier sites which are dominated by pin cherry in the earliest stages, then by red and white oak and red maple (Figure 9B). On the wetter sites sugar maple develops during the first decades but declines almost to the point of

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[9] Based on analyses of existing forests stands by remote sensing, carried out by F. Hall, D.B. Botkin, D. Strebel, and S. Goetz.

[10] The general trend of our results showing forest responses to double CO_2 over a 100 year period are similar to those of another study of Michigan forests by Solomon and West, using a model derived from JABOWA which does consider climate interaction and immediate doubling of CO_2. However, Solomon and West used only the GFDL model, projecting a more severe warming and drying trend then the GISS models and predicting future forests composed of even drier species like pine (Solomon and West, 1987). Simulating forest ecosystem responses to expected climate change in Eastern North America: Applications to decision making in the forest industry. In: The Greenhouse Effect, Climate Change, and U.S. Forests. W.E. Shands and J.S. Hoffman, eds. The Conservation Foundation, Wash., D.C. pp. 189-217).

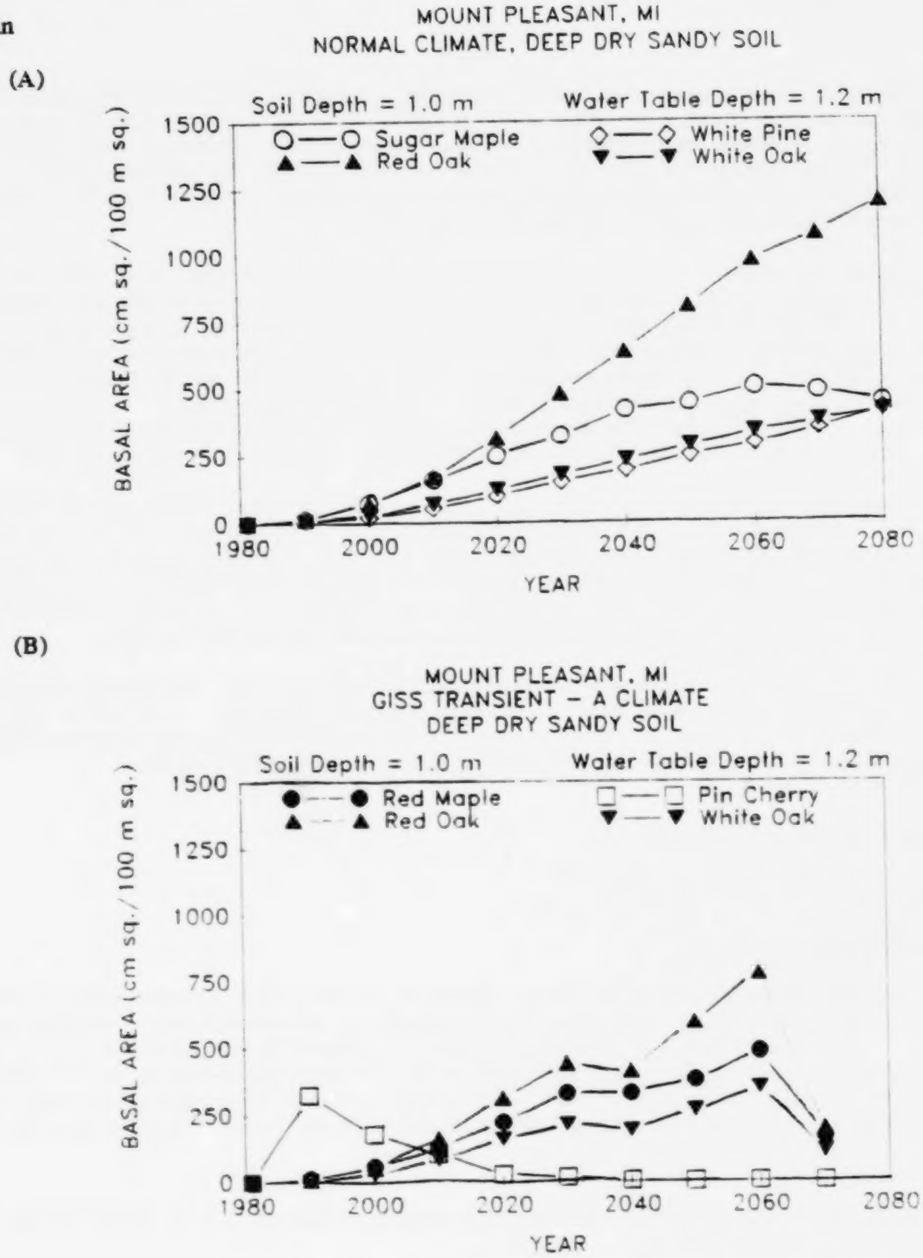


Figure 9. Development of a forest from clearing in the southern portion of the Great Lake States. The forest represented here is near Mt. Pleasant, MI, on a deep, dry, well-drained, sandy soil for (A) north (1951-1980 Mt. Pleasant weather records) and (B) these records as modified by the GISS transient A climate, represent the transition from current conditions to climate under increasing CO_2 concentrations.

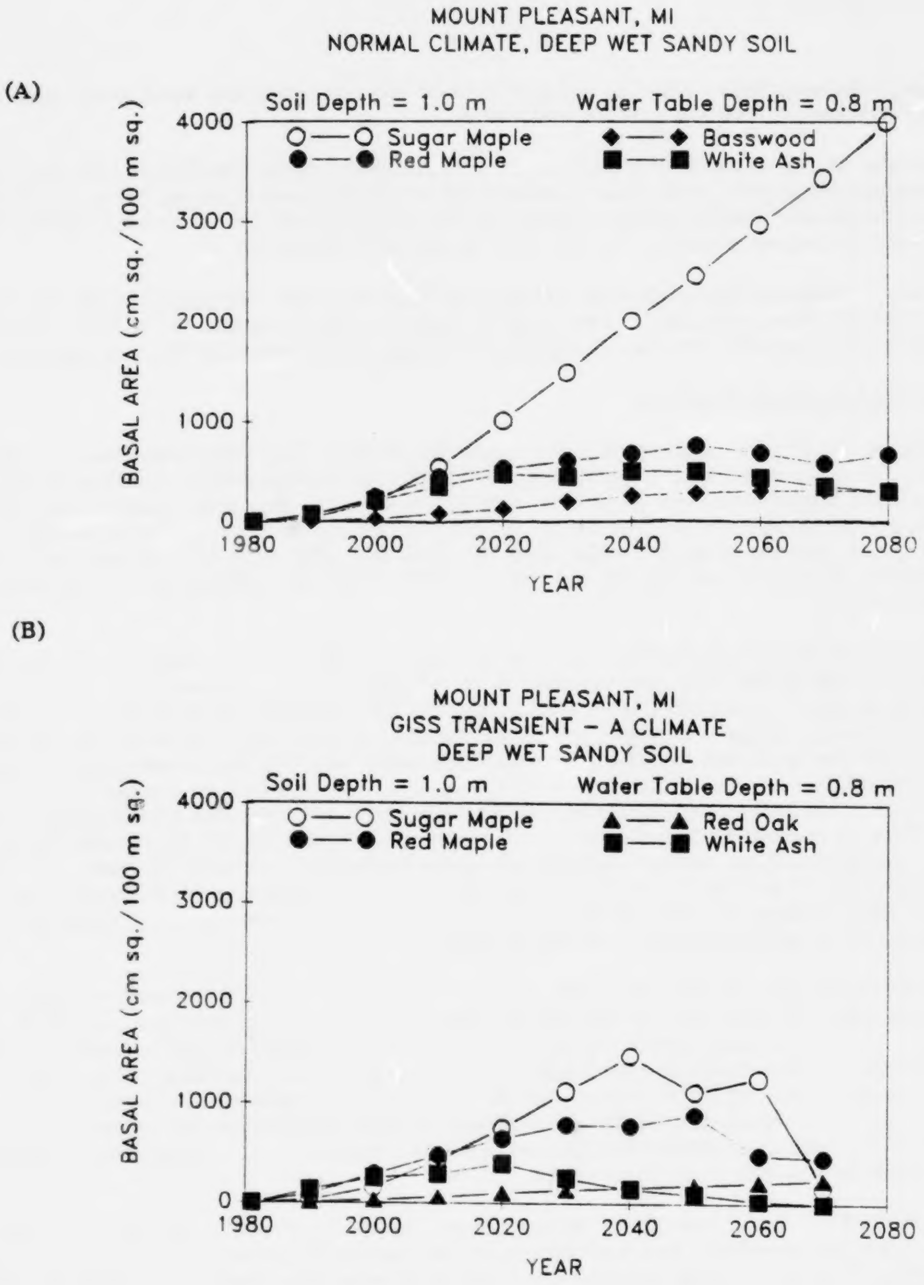


Figure 10. Development of a forest from clearing in the southern portion of the Great Lake States. The forest represented here is near Mt. Pleasant, MI, on a deep, wet, well-drained, sandy soil for (A) north (1951-1980 Mt. Pleasant weather records) and (B) these records as modified by the GISS transient A climate, represent the transition from current conditions to climate under increasing CO_2 concentrations.

disappearance by the end (Figure 10B). In transient B, which provides projections for 60 years, sugar maple follows a similar pattern as transient A on the wetter sites.

On the drier site, forest productivity under transient A climate during the first 50 years following clearing matches the normal productivity, while under transient B the productivity exceeds normal for the first 50 years. Afterwards, as the climatic warming effects increase, there is a decline by year 2040 under both transient A and transient B, with the biomass reaching a very low value by year 2070 (Figure 11).

The forest represented here is near Mt. Pleasant, MI on a deep, dry, well-drained, sandy soil for (A) north (1951-1980 Mt. Pleasant weather records), and (B) these records as modified by the GISS transient A climate, represent the transition from current conditions to climate under increasing CO_2 concentrations.

Comparison with Steady-State Conditions

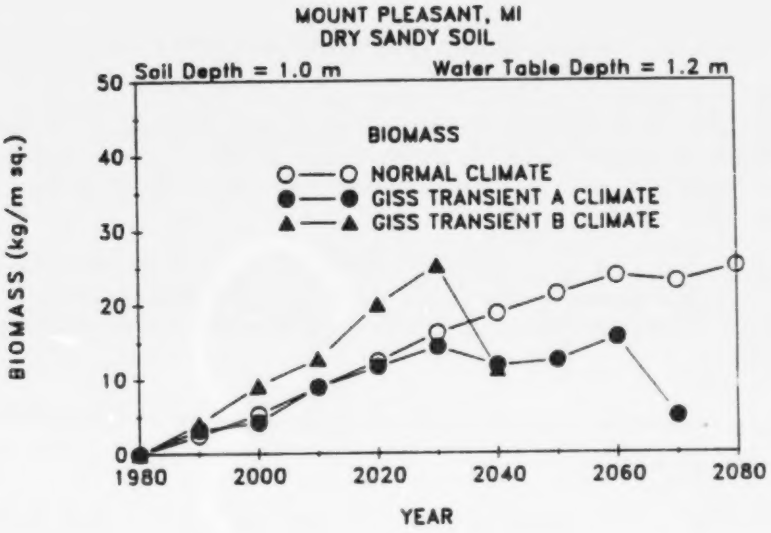
The transient results are consistent with the projections for twice CO_2 steady-state climates under all three models. This is illustrated here for results from the Mt. Pleasant weather records. The three steady-state models differ in the magnitude of their projections, with GFDL giving the most severe changes and OSU the mildest changes. For example, on the drier site for the Mt. Pleasant region, total biomass accumulation after 100 years of growth exceeds 20 kg/m^2, while under the GISS and OSU twice CO_2 climates the biomass accumulation after 100 years is less than 10, and under the GFDL twice CO_2 climate there is negligible tree biomass (Figure 12A).

There is greater biomass accumulation on the wetter site under all steady-state climates, but the GFDL climate leads to a much smaller value, approximately 10 kg/m^2 compared to the normal forest whose biomass is approximately 50 kg/m^2 at year 100 (Figure 12B). Under dry soil conditions, the three climate models lead to predictions of a major change in dominant species and therefore in forest type, from a northern hardwood-oak transition to an oak forest with red maple. With the GISS model twice CO_2 steady-state climate (Table 1), the forest model results in an open savannah forest of low biomass (dropping from an average of 25 kg/m^2 to less than 2 kg/m^2 of tree biomass) dominated by oaks which are sparse and small even after 100 years (Figures 9 and 10). While the normal forest would have commercially useful hardwoods, the forest under the steady-state altered climate would not produce commercially useful hardwoods even after 100 years. From an ecological perspective, this is a very severe effect. Under such a shift, wildlife species would change from those adapted to the more northern closed forests to those adapted to grassland- savannah. Sugar maple and other dominant species of the northern hardwoods forests disappear.

The GFDL model gives an even more extreme effect; remaining at year 100 are many very small trees which contribute almost no biomass to the plot; red and white oak and red maple contribute most of the small amount of basal area. For example, even at year 100 there is only 13.6 $cm^2/100m^2$ red oak, equivalent to a single tree with a diameter of 4 centimeters at breast height (a sapling in other words). Assuming grasses could survive under these conditions, then the GFDL predicts that the forest would be converted to a sparse savannah or a grassland with sparse, very small trees (Table 1). Eventually, it is also possible that tree species with an even more southern distribution might migrate into the area. This last possibility could be investigated by expanding the current species list available to the forest model.

Although the OSU model projects the mildest climatic change, its twice CO_2 climate results with the forest model in a sparse open forest with 6 ± 3 kg/m^2, a forest that would appear to vary from a savannah to an open woodland. Consistent among the projections for the three steady-state climate is a considerable decline in biomass accumulation after the third decade on the drier site (Figure 12A) and after the seventh decade on the wetter site (Figure 12B). The GISS and GFDL climates result in negligible biomass accumulation on the drier site for all time periods. This suggests that upland areas would typically be converted to savannahs or open woodlands.

(A)



(B)

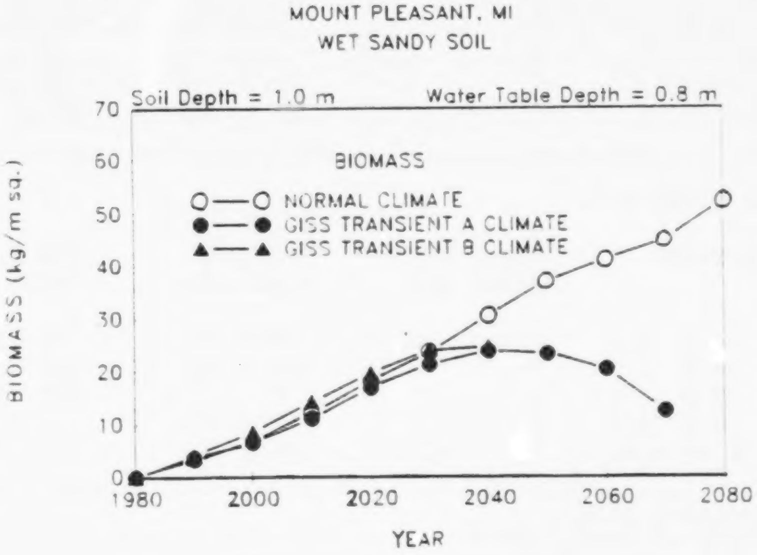


Figure 11. Biomass changes during the development of a forest from clearing in the southern portion of the Great Lake States. The forest represented here is near Mt. Pleasant, MI, on a deep, dry, well-drained, sandy soil for (A) north (1951-1980 Mt. Pleasant weather records) and (B) these records as modified by the GISS transient A climate. represent the transition from current conditions to climate under increasing CO_2 concentrations.

Table 1. Forest Conditions After 100 Years of Growth

Forest conditions after 100 years of growth from clearing on a deep dry sandy soil. Soil depth 1.0 m; depth to water table 1.2 m (A) (dry soil) and (B) 0.8 m (wet soil); soil moisture holding capacity 150.00 mm/m of soil; soil nitrogen 150.

Treatments are: Normal: growth using Mt. Pleasant, MI. 1951-1980 weather records; GISS, GFDL, and OSU: steady-state twice CO_2 climates as modified by each of these models; TR-A, a transient projected by the GISS model from current climate to future climate.

(A) Deep Dry Sandy Soil

TREATMENT	BIOMASS	SUGAR MAPLE BASAL AREA.	RED OAK BASAL AREA	RED MAPLE BASAL AREA
NORMAL	25 ± 3.7	444 ± 53	1193 ± 152	136 ± 71
GISS	1.9 ± 0.3	0	118 ± 11	150 ± 24
GFDL	0.1 ± 0.02	0	6 ± 1	10 ± 1
OSU	6.8 ± 3.1	0	232 ± 49	323 ± 122
TR-A[a]	4.9 ± 2.4	0	196 ± 53	164 ± 83

(B) Deep Wet Sandy Soil

TREATMENT	BIOMASS	SUGAR MAPLE BASAL AREA.	RED OAK BASAL AREA	RED MAPLE BASAL AREA
NORMAL	52 ± 2.0	4008 ± 166	108 ± 23	664 ± 199
GISS	33 ± 4.9	0	176 ± 34	2117 ± 389
GFDL	12 ± 1.9	0	53 ± 7	1097 ± 157
OSU	28 ± 3.5	0	231 ± 39	1177 ± 292
TR-A[a]	12 ± 2.0	157 ± 33	239 ± 85	458 ± 165

Units are: Biomass Kg/m^2
Density: Number of trees/ 100 m^2;
B.A.: basal area (cross sectional area) $cm^2/100m^2$
(all values are mean ± S.E. for 60 replicates).

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[a] Note that this transient climate model output is available for only 90 years; year 90 is shown here for comparative purposes.

On deep, well-watered sites with sandy soils (soils with a saturated zone but a well aerated layer above), the forest under normal conditions is transitional with sugar maple and red maple with other wetland and floodplain species including white ash and hemlock, suggesting abundant water for tree growth (Table 2). The GISS model twice CO_2 climate results in a forest dominated heavily by red maple with some oaks present; none of the northern hardwood forest species occur (Table 2). Red maple increases in basal area under the three steady-state twice CO_2 climate regimes.

Under the 1951-1980 actual climate, the normal forest, sugar maple continues to increase throughout the 100 years, while no sugar maple grows in any of the steady-state twice CO_2 climates. Even in transient A climate, which contains projections for 90 years, sugar maple declines almost to the point of disappearance by the end. Only in transient B, which provides projections for 60 years, does sugar maple remain (transient A suggests little change in the abundance of sugar maple by the end of 60 years).

Again the GFDL model shows a more severe effect (Table 2). Red maple and white and red oaks are again dominant at year 100, but the biomass averages 12 ± 4 kg/m^2 (mean ± 95% confidence interval) in comparison to 33 ± 10 kg/m^2 under the GISS twice CO_2 steady-state climate, 27 ± 7 kg/m^2 under the GFDL twice CO_2 steady-state climate, and 52 ± 4 kg/m^2 projected for the 1951-1980 climate.

Under the GFDL twice CO_2 steady-state climate, the basal area of the dominant species, red maple is half that under the GISS climate. Under the OSU twice CO_2 steady-state, the forest has a little more than half the biomass of the normal forest, but the basal area on red oak remains about the same as under the GFDL climate.

The results for the northern portion of the area are similarly consistent between the transients and the steady-state climatic projections, and the steady-state climates maintain the same order of severity for the forests, with GFDL given the largest and most severe change, GISS next, and OSU the least severe.

ECONOMIC FORESTRY

The results described here concern harvests of forests allowed to undergo natural regeneration, a common practice for hardwood forests of the Great Lake States. Even under the best of conditions, the species composition may change from a forest with the potential for growth of sugar maple, yellow birch, and white pine to a forest with a potential to grow red and white oak. On drier sites, forest productivity may drop below economically useful levels. For example, under the GISS twice CO_2 steady-state climate, the biomass of 100-year-old stands on sandy soils drops to 1/10th that of the normal forest, to below 2 kg/m^2 above ground biomass (see Table 3).

A 50 year rotation forest with natural regeneration produces an average of 13 kg/m^2 in the normal forest but less than 2 kg/m^2 under the GISS twice CO_2 steady-state climate. Under the GFDL there is no harvestable forest biomass at year 50 or at year 100 on the drier site (Table 3). On the wetter site most of the biomass is in red maple, a species not of economic importance (Table 3). Thus the forest model projects strong effects under the modified climates for commercial forest productivity.

The reduction in number of days with hard frosts may have implications for commercial fruit crops including cherry and apple. The increase in temperature and resulting increase in actual evapotranspiration relative to potential evapotranspiration would also affect orchards, requiring a great increase in irrigation water if the crops were to be continued. It is important to investigate the possible effects of the climate change on orchards.

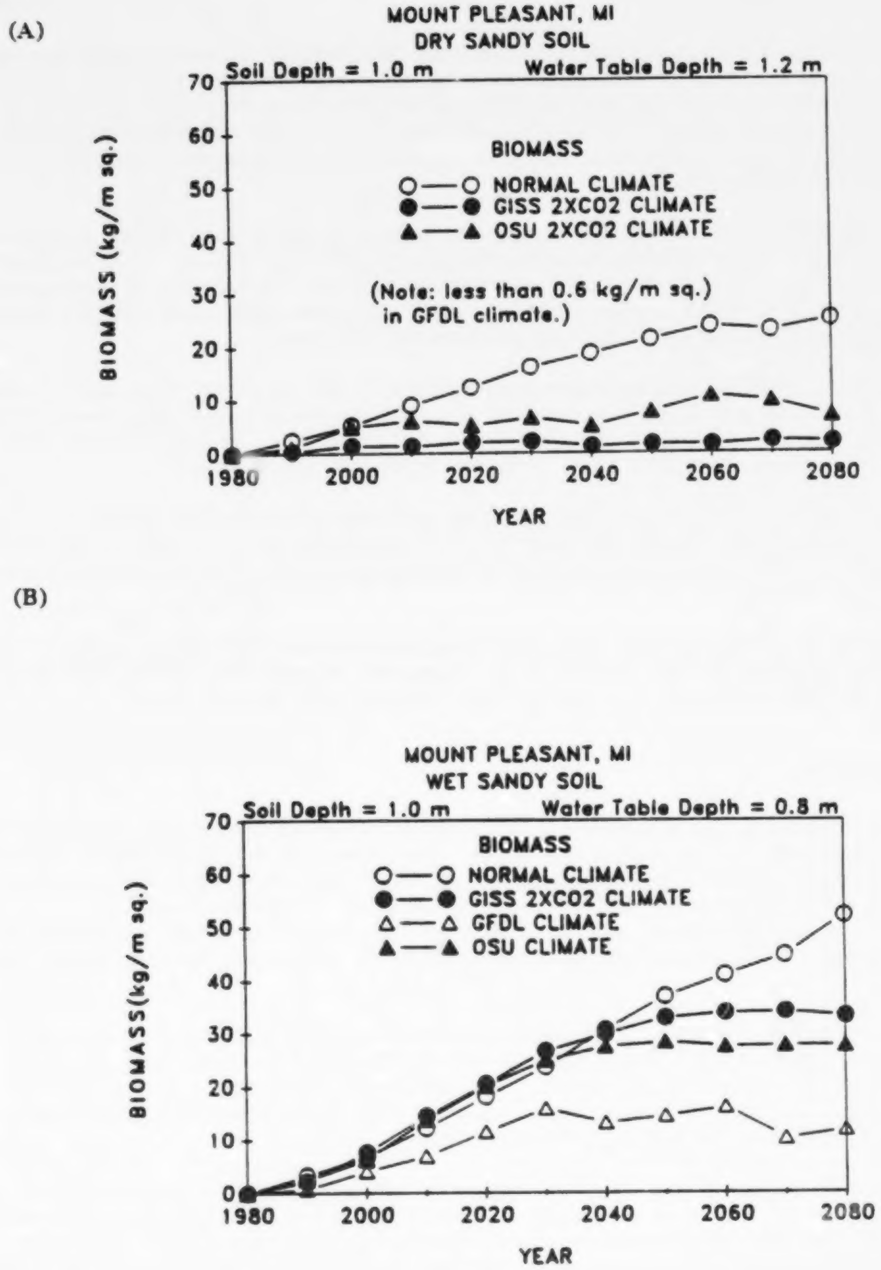

Figure 12. Biomass accumulation during 100 years of growth under stead-state climates for the region near Mt. Pleasant, MI, on (a) dry sandy soil, and (B) wet sandy soil.

Table 2
DOMINANT TREE SPECIES FOR MOUNT PLEASANT, MI
Deep Relatively Wet Sandy Soil YEAR: 100

MOUNT PLEASANT, MI
1951-1980 WEATHER DATA
Depth to the Water Table 0.8 m; Soil Depth 1.0 m; soil moisture holding capacity 150.00 mm/m of soil; soil nitrogen 150; 60 replicates.

DOMINANT TREE SPECIES		DENSITY (#/100m^2)		BASAL AREA (cm^2/100m^2)	
		AVERAGE	95%CI	AVERAGE	95%CI
(1)	NORMAL CO2				
1	SUGAR MAPLE	10.5	.77	4008.3	332.6
13	RED MAPLE	.2	.12	664.1	397.3
4	WHITE ASH	.2	.13	298.4	198.8
36	BASSWOOD	2.7	.45	299.9	111.2
30	HEMLOCK	2.7	.50	179.2	58.7
28	NORTHERN RED OAK	.5	.22	107.8	46.3
26	TREMBLING ASPEN	.1	.08	88.9	71.4
(2)	TWICE CO_2 (GISS MODEL)				
13	RED MAPLE	1.3	.64	2116.9	777.0
39	BLACK CHERRY	1.7	.87	334.5	136.0
27	WHITE OAK	2.2	.56	260.4	67.5
28	NORTHERN RED OAK	1.6	.64	176.3	68.7
(3)	TWICE CO_2 (GFDL MODEL)				
13	RED MAPLE	2.4	.55	1097.2	314.1
27	WHITE OAK	3.8	.65	96.7	21.5
28	NORTHERN RED OAK	2.4	.47	53.1	14.8
(4)	TWICE CO_2 (OSU MODEL)				
13	RED MAPLE	.5	.26	1177.2	583.2
39	BLACK CHERRY	1.7	.56	1001.4	271.4
27	WHITE OAK	1.8	.42	267.1	65.8
28	NORTHERN RED OAK	1.1	.46	230.7	77.1
(5)	TRANSIENT MODEL A (YEAR 90)[a]				
13	RED MAPLE	.3	.19	458.4	329.3
39	BLACK CHERRY	.9	.33	381.4	120.6
28	NORTHERN RED OAK	1.0	.26	238.9	70.1
1	SUGAR MAPLE	.6	.20	156.6	65.0
27	WHITE OAK	1.1	.46	84.7	28.9

---

[a] Note that this transient climate model output is available for only 90 years; year 90 is show here for comparative purposes.

Table 3 EFFECTS ON ECONOMIC FORESTRY

Biomass Production After 50 Years Growth Following Clearcut
Based on weather records from Mount Pleasant, Michigan

(A) Deep Dry Sandy Soil

MOUNT PLEASANT, MI
1951-1980 WEATHER DATA
Depth to the Water Table 1.2 m; Soil Depth 1.0 m
soil moisture holding capacity 150.00 mm/m of soil;
soil nitrogen 150; 60 replicates.

	BIOMASS (kg/m^2) ABOVE GROUND	
	MEAN	**95%CI**
NORMAL (Dominant species aspen, red oak and sugar maple)	13.4	1.4
TWICE CO_2 GISS (Dominant species red maple and red oak)	1.8	0.4
TWICE CO_2 GFDL (Dominant species: pin cherry, choke cherry)	0.07	0.007
TWICE CO_2 OSU (Dominant species: red oak and red maple)	9.3	1.6

(B) Deep Relatively Wet Sandy Soil

Depth to the Water Table 0.8 m; Soil Depth 1.0 m
soil moisture holding capacity 150.00 mm/m of soil;
soil nitrogen 150; 60 replicates.

	BIOMASS (kg/m^2) ABOVE GROUND	
	MEAN	**95%CI**
NORMAL (Dominant species sugar maple and red maple)	19.4	1.6
TWICE CO_2 GISS (Dominant species red maple and black cherry)	26.0	3.6
TWICE CO_2 GFDL (Dominant species: red maple)	13.0	1.8
TWICE CO_2 OSU (Dominant species: red maple and black cherry)	21.	3.8

LIMITS OF THE RESULTS AND RESEARCH NEEDS

The time and funds available for this study placed a limit on the work that could be done, and it is not yet known how sensitive the results may be to specific factors. This work merely scratches the surface of the effects of climate on forests of the Great Lake States, but points out the very strong and important changes that result from the projected climatic effects of carbon dioxide increase. Wise planning would require additional research. There are six ways that the work should be extended:

(1) Test the sensitivity of the results to the value of intrinsic parameters in the forest growth model, such as the maximum longevity of trees, the temperature limits of growth.

In particular, it is especially important to determine how sensitive the projected timing of changes under the transient climatic regimes is to specific values of species parameters in the forest models and to key assumptions in the climate models.

(2) Test the sensitivity of the results to certain extrinsic parameters of the model, such as the choice of 1951-1980 weather records as a basis for simulation of future climates, the use of ratios of control, and modified climates to determine climatic change parameters.

(3) Also test the response of the forest model to the effects of different rates of seed dispersal.

(4) Extend the work to more soils with a wider variety of soils in regard to soil depth, texture, and fertility. Choose additional sites for which good soil information exists. In areas where commercial forestry is important, investigate the effects on forests with representative soils of those areas at a number of harvesting periods.

(5) Extend the model by adding more species representing those found even farther south to determine the forest response to the altered weather conditions if these could migrate into the area.

(6) Consider the interaction between the climatic affects considered here and other environmental factors including fire, pathogens, insects, air pollution, UV-B radiation fluxes, acid rain and gaseous oxidants, human management and human-induced disturbances, as well as the frequency, intensity, and duration of extreme weather events including wind, flooding, and drought.

(7) Consider the effects of various forestry methods or new practices such as irrigation to increase forest yield.

POLICY IMPLICATIONS

Forestry and recreation in forested areas are important in the Great Lake States and generally considered to provide an important future economic resource. For example, in 1980 the Governor of Michigan held a major state conference on forest products; the conference concluded that the forests provided a "vast" resource covering more than half of the state (more than 19 million acres), and that "current productivity could be doubled with good forest management practices," and could be a basis for "considerable expansion" of the forest industry. In 1975, forest industry in Michigan alone produced $1.2 billion and provided 64,000 jobs, and the conference projected that this could be increased $3.4 billion, adding 21,000 new jobs (Milliken, 1980).

The results of the simulations reported here suggest that it is necessary to re-evaluate potential forest productivity in light of climatic change. These results indicate dramatic changes would occur even on good, well-drained soils which are currently the sites of most commercial forest production. On such sites, total wood production under a 50-year rotation could drop under the twice CO_2 steady-state climates in the southern part of the area to essentially nothing, as projected with GFDL steady-state climate, or to as little as 70% of the current yields, as projected with the OSU model. In either case, the effect would be economically severe. On the positive side, some lowland forests would become better drained and their wood production might increase, as projected using the GISS and OSU models. (In the worst case these lowland forests would decrease by about 30% as projected using the GFDL climate.) Whether the putative increase on lowland sites could compensate for the decrease in upland sites would have to be evaluated in future work.

In all cases, there may be a major shift in species composition. Currently the forest industry in the Great Lake States is adapted for a certain complement of species, primarily for softwoods used in the production of paper pulp and construction materials. In the southern portion of the area, the species that would become most economically important under twice CO_2 steady-state climate would be hardwoods such as oaks, useful for furniture and other decorative purposes. Moreover, the most economically valuable of these more southern species, red oak, would have a much longer rotation time with harvesting less frequent than for softwoods. Thus there would be a major shift in the character of the forest industry whose costs should be evaluated; the shift would require different equipment and markets.

Michigan and Minnesota, like other Great Lake States, have a large tourist industry centered around their forests and the wildlife and waterways within the forests, which in turn depend on forest characteristics for their maintenance. The projected change in species composition may affect all aspects of recreation, especially wildlife habitat, and the kind and quality of fisheries in lakes and streams. While there can be considerable recreation in the kinds of forests that would result, the character of the recreation would change. For example, in the southern portion of the region, people would hike in oak forests and oak savannahs rather than in northern hardwoods or boreal forests. There would be different wildlife, and one would expect less canoeing. Whether this would increase, decrease, or leave recreational use at current levels should be examined.

The above statements concern the projections for twice CO_2 steady-state climates. On the more positive side, the transition from current forests would take place comparatively slowly in human terms (although these are extremely rapid in terms of forest growth, more rapid than effects we have examined previously for periods during the last 10,000 years). However, as the climatic stresses on the trees increase they will become more susceptible to insect outbreaks and diseases. For example, balsam fir under stress are much more susceptible and likely to attract the spruce budworm, which kills the trees; outbreaks typically start in stands of stressed trees, triggering large outbreaks in otherwise healthy forests. In addition, forests with an increasing number of dead trees and increasing percentage of stressed trees will provide greater fuel for fire. When combined with a generally drier soil, these factors could increase the probability of fires, and lead to additional decreases in economic yield and to more rapid changes in recreational attributes. The effects of such disturbances should be investigated.

All of these implications are currently based on simulations of forest growth in two regions on two soil types. Until more areas can be considered with the forest model, all implications must be treated with great caution.

Our results contrast with previous qualitative conjectures that forest production would be uniformly increased by CO_2 increases in the atmosphere. These conjectures are based on laboratory experiments which show that well-fertilized and well-watered plants undergo great increases in production under CO_2-elevated atmospheres. We do not expect this effect to be significant for two reasons: (1) the water limitation will prevent any substantial CO_2 fertilization response; and (2) as we have shown elsewhere (Botkin et al., 1973), competition among trees for light in a mixed species forest buffers the forest against CO_2 fertilization. The net growth increase in an entire forest is thus much less than that of a single plant in a laboratory. With competition for limited water and light, as well as for specific chemical elements in the soil such as nitrogen, the direct response to CO_2 fertilization is likely to be insignificant; however, explicit consideration of the combined effects of changes in temperature, rainfall, and CO_2 concentration should be investigated.

These results are restricted to direct climatic change on two soil types. No other independent effects, such as the effects of other air pollutants or the direct effect of CO_2 atmospheric concentration on tree growth, were taken into account. It is important to consider the combined impact of these processes, including direct fertilization effects of CO_2 on tree growth and effects of acid rain and gaseous oxidants on tree growth, and to consider these for more soil types. The potential for such projections now exists.

SUMMARY

The general pattern that emerges from these findings is that the CO_2-induced climatic change leads not only to much warmer, but also to much drier conditions than occur at present; although rainfall increases, total evapotranspiration increases more and as a result less soil moisture remains for tree growth. As a consequence, wetter sites become warmer and somewhat better drained; sandy, wetter sites are able to support forests, but these are characteristic of areas to the south and there is a drop in total biomass. The dominant species shift from those with commercial value to those of little commercial value. On drier sites, the climatic shift is severe enough to convert substantial forests to open woodlands, savannahs, or grasslands with small scattered trees.

These results are projected for good sites for forest growth. The soils are very deep and well drained, and (although relatively sandy under the 1951-1980 climate) they are moderately fertile and well to very well watered; the wetter sites have only a minimal amount of saturated soil. Similar, sandy, glacial-derived soils are not uncommon in the region around Mt. Pleasant, MI. Thus the projections represent the more optimistic conditions than are to be expected. Additional trials with the models on a greater variety of soils would of course be of considerable utility to broaden the scope and increase the accuracy of the projections.

It is important to note that previous speculations about the effects of CO_2 increases on forest growth have emphasized the direct "fertilization" effect of that increase: in laboratory experiments, increasing CO_2 increases the growth rates of individual trees. Thus some authorities have speculated that the CO_2 increase will simply increase total forest productivity. However, we showed much earlier (Botkin et al., 1973) that competition among trees in a mixed-species forest would result in a much smaller effect than predicted from a laboratory trial with a single tree. The results presented here suggest that the climatic changes are very strong; our judgment based on past modeling experience is that the climatic effects would more than compensate for any CO_2 enhancement effect; however, the combined effects of climate change and CO_2 fertilization should be studied.

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FOREST RESPONSE TO CLIMATIC CHANGE:
A SIMULATION STUDY FOR SOUTHEASTERN FORESTS

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FINDINGS[1]

We used a forest simulation model to explore the effects of climatic variability on southeastern forests. All climate-change scenarios (GISS, OSU, and GFDL $2xCO_2$) predict a warming and drying climate. This in turn predicts the northward migration of forests, such that areas now characterized as oak-pine types would be replaced by more southern types characterized by loblolly pine. Based on climatic correlates of present-day forest distributions, the extreme southeastern forest types could not be supported by projected climates; the peculiar (confounded) biogeographic context of these sites does not allow us to confidently predict their fate.

Transient climate scenarios suggest that the short-term response to rapid climate change would be a period of synchronous stress mortality, resulting in forest declines in all simulated cases. The magnitude of this response would depend on the magnitude of climate change relative to species tolerances, and on the suddenness of the climate change. The timing of forest decline would likely depend on local weather patterns, with episodic mortality triggered by a period of unusually stressful years. Susceptibility to climatic stress depends on stand age and condition, with older or already stressed stands being especially vulnerable to additional climatic stress. These factors in combination make it unlikely that we could confidently detect or accurately predict a short-term response to climate change for any particular case.

This study illustrates our uncertainty about the proximate mechanisms that govern forest response to climatic variability. We suggest research priorities for further studies, toward a more fundamental understanding of the mechanisms and consequences of environmental constraints on forest ecosystems. Perhaps the most critical uncertainty in this study concerns seed dispersal and species migration rates; these are critical to predicting forest response to transient climate, and we have little capability to estimate these effects.

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[1] Although the information in this report has been partly funded by the U.S. Environmental Protection Agency under Contract No. CR-814610-01-0, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

CHAPTER 1

INTRODUCTION

In this report we provide a preliminary assessment of the potential effects of climatic variability on forests of the southeastern United States. We consider a spectrum of forest types throughout the southeast, ranging from oak-pine, through southern mixed forest of the Piedmont, to coastal-plain elements of the southeastern evergreen forest. Within each forest type, we focus first on upland sites; for the coastal plain we examine bottomland forests as well.

In the following sections we detail the rationale and methods we use to relate forest dynamics to climatic variation, present simulation results from a variety of climatic scenarios, and discuss the implications of these results. Our discussion underscores the uncertainties in our current understanding and suggests priorities for further studies of forest response to climatic variability.

FOREST TYPES AND STUDY SITES

This study is concerned primarily with upland forests of the Southeast. In the southern Appalachians, these forests encompass oak-pine, oak-hickory, oak-chestnut, as well as other variants of southern mixed forest types as classified by Braun (1950), Kuchler (1964), and Bailey (1976). In terms of potential vegetation cover, these forest types represent more land area in the continental United States than any other forest (Eyre, 1980). Key species include upland oaks (Quercus alba, Q. rubra, Q. velutina), hickories (Carya cordiformis, C. glabra, C. ovalis, C. ovata, and C. tomentosa), and shortleaf pine (Pinus echinata). Through the Piedmont and onto the coastal plain, indicator species include sweetgum (Liquidambar styraciflua), black gum (Nyssa sylvatica), southern oaks (Q. falcata, Q. shumardii), and especially loblolly pine (P. taeda). The southern pinelands dominated by shortleaf and loblolly pines are by far the most important commercial forests in the eastern United States.

This spectrum of forest types was represented in this study by four locations: Knoxville, Tennessee (35.8° latitude (lat), 89.8° longitude (lon), representing Appalachian oak-pine forests; Florence, South Carolina (34.2° lat, 79.7° lon) in the northern coastal plain; Macon, Georgia (32.7° lat, 83.7° lon), on the southern margin of the Piedmont; and Vicksburg, Mississippi (32.4° lat, 90.0° lon), near the western margin of the coastal plain (Figure 1). The latter three sites represent a east-west gradient across the loblolly pine forest type, from mesic to more xeric climatic regimes. It should be emphasized that the selection of study sites was largely constrained by the availability of long-term weather records; we do not intend to make specific statements about these particular locations, and the preliminary results of this study should not be overinterpreted in this respect.

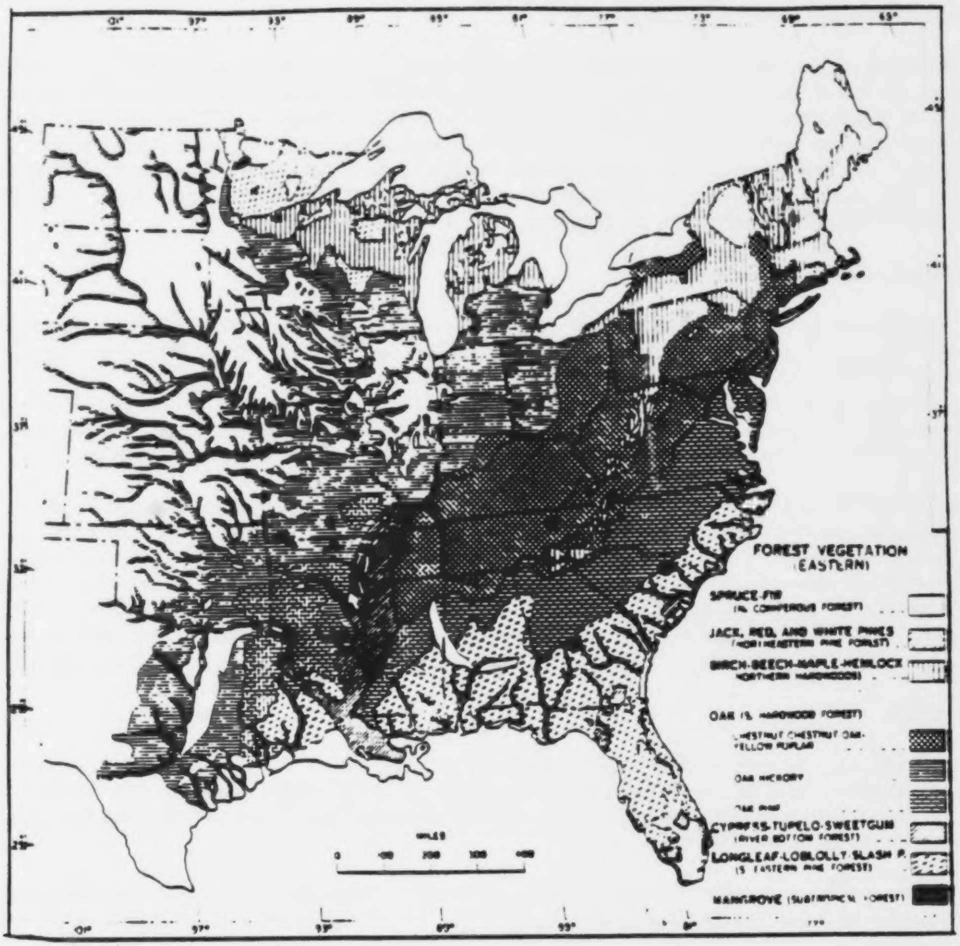

FOREST VEGETATION (EASTERN)
SPRUCE-FIR (N. CONIFEROUS FOREST)
JACK, RED, AND WHITE PINES (NORTHEASTERN PINE FOREST)
BIRCH-BEECH-MAPLE-HEMLOCK (NORTHERN HARDWOODS)
OAK (S. HARDWOOD FOREST)
CHESTNUT-CHESTNUT OAK-YELLOW POPLAR
OAK-HICKORY
OAK-PINE
CYPRESS-TUPELO-SWEETGUM (RIVER BOTTOM FOREST)
LONGLEAF-LOBLOLLY-SLASH P. (S. EASTERN PINE FOREST)
MANGROVE (SUBTROPICAL FOREST)
MILES
0
100
200
300
400

Figure 1. Forest vegetation of the eastern United States (adapted from Fowells, 1965). Study sites are indicated in east Tennessee, South Carolina, Georgia, and Mississippi.

CHAPTER 2

METHODS

This study follows the precedent set by a number of previous studies in using forest simulation models to explore the response of forests to climate-mediated environmental drivers (Solomon 1986, Solomon et al. 1981, Solomon et al. 1984, Solomon and Tharp 1985, Solomon and Webb 1985, Davis and Botkin 1985, Pastor and Post 1988; see also Botkin et al. 1972, Shugart 1984). While these studies varied in purpose and detail, they share a common rationale and method; conveniently, they also have used similar versions of the same basic forest model (Botkin et al. 1972, Shugart 1984).

Modeling forest response to an environmental driver requires, in the simplest sense (1) a description of how trees respond to the environmental factor of interest, and (2) a means to generate or provide reasonable scenarios of variability in the environmental driver. While some aspects of this approach may seem rather complicated (perhaps even realistic), it should be emphasized that the results of these studies should be interpreted at the level of these basic steps involved in their implementation. That is, model output should be interpreted as the consequences or implications of the assumptions in the model, rather than as precise predictions of reality. We return to this theme at a later point.

FOREST SIMULATION MODEL

The model used in this study was ZELIG, a versatile forest simulator developed for applications concerned with spatial patterns occurring at scales larger than the forest gap. The model is an individual-based "gap model" (Shugart and West 1980) derived from the FORET model of Shugart and West (1977). Gap models simulate forest dynamics by modeling the demographics of each individual tree on a small model plot corresponding to the area of a forest gap. These models have been especially useful in simulating the dynamics of mixed-age, mixed-species forest stands (Botkin et al. 1972; Shugart and West 1980, Shugart 1984).

Like its parent and sibling models, ZELIG simulates forest dynamics by accounting the establishment, annual diameter growth, and mortality of each individual tree in the simulated forest. The basic approach in modeling each of these demographic processes is to begin with a maximum potential behavior (e.g., inseeding rate, diameter increment, survival probability) and subsequently modify this potential according to the status of the individual tree in the context of the modeled gap. The contextual contraints modeled in ZELIG include available light, temperature, soil moisture, and soil fertility. The ZELIG model is documented in more detail in the Appendix. The 45 tree species included in these simulations are summarized in Appendix Table A.1.

SCENARIOS

Upland forests at each location were simulated as growing on the same soil type, in order to control this source of variation in modeled forest dynamics. Thus, the ZELIG model as implemented for this study is wholly driven by weather data provided as input data. Baseline weather data comprised monthly precipitation and temperatures for the years 1951-1980.

Climate-change scenarios were derived from GISS, GFDL, and OSU model output as provided by NCAR. Implementation of these scenarios was as dictated by EPA. For the GISS scenario, data conversions were based on the grid point at 35.22° N lat, 80.00° W lon; GFDL conversions were based on grid point 33.33° lat, 82.50° lon; the OSU grid point was 36° lat, 85° lon. Because of the coarse resolution of the GCM-model grid cells, the same conversion ratios were used for all four sites. A single transient scenario was considered, GISS Transient A. Relative to previous simulation studies of this sort, this study considers alternative steady-state climates under 2xCO_2 (represented by three GCMs), and emphasizes especially the transient climate change as predicted by the GISS model. This is in contrast to previous studies, which have assumed a single steady-state climate under altered CO_2 or have used a linearly interpolated transient climate (e.g., Solomon 1986, Pastor and Post 1988).

SIMULATIONS

In simulations, the 30-year base weather was concatenated to yield climate scenarios that were of sufficient length to elicit a meaningful forest response. In each case, simulations were run for 200 years. The initial few decades illustrate successional dynamics under each scenario, while the later years suggest trends in more mature forests. Results reported here are averages of 50 replicate model plots.

The design of this study was to run four climate scenarios for an upland soil at each location (baseline, GISS, GFDL, and OSU), as well as a bottomland site for the south-central location in Georgia. Modifications to this design are explained more fully where applicable.

CHAPTER 3

RESULTS

Before presenting the results of the several forest simulations, it will be instructive to summarize the climate-change scenarios in terms of their computed drought-day and growing degree-day indices. Because these are the effective environmental constraints incorporated in the forest model, a knowledge of species tolerances to these indices can provide a helpful preview of model results. Following this preview, the model results will be presented in more detail.

CLIMATE-CHANGE SCENARIOS

All three climate models predict a warming and drying as compared to current conditions. The models differ in that the GISS prediction is for moderate warming with a concomitant increase in precipitation, while GFDL predicts a warming with a decrease in growing-season precipitation; OSU predicts GISS-like temperatures and GFDL-like precipitation.

In terms of the constraints computed by the forest model, all three scenarios predict a large increase in annual growing-degree sums, while there is some variability in predicted drought-day indices (Table 1). For reference, we should note that no tree species simulated in the model can tolerate a drought-day index greater than 0.6 (indexing the proportion of the growing season under drought conditions); few species can tolerate a value greater than 0.5, and most species show significant growth reductions if the drought index is greater than 0.3 (refer again to Appendix Table A.1). A drought index of ≈0.5 (half the growing season under drought conditions) roughly corresponds to the western margin of the eastern deciduous forest.

Similarly, few tree species of the southern mixed forest are found under temperature regimes of more than ≈6000 degree-days (a 5500-GDD isopleth roughly parallels the Gulf coast). We should note that our estimates of heat-sum tolerances of some of these species are thus not very confident, because their distributions are limited by geographic constraints (the Gulf) rather than climatological factors. We return to this point later in this discussion, but note here that the model will grow only marginal forests under temperature regimes of more than ≈6000 degree-days.

FOREST DYNAMICS UNDER CLIMATE CHANGE

The 200-year simulations cannot indicate clearly which species will ultimately come to dominate southern uplands under the various climate scenarios, but the model results do indicate successional trajectories under these regimes. In general, the baseline simulations reproduce major seral trends for these southeastern forests: shortleaf pine in the more northern oak-pine forests of east Tennessee, and loblolly pine throughout the more southern forest types. While this is encouraging, for our purposes it is sufficient that the model provide a useful framework of reference for further simulations. The following sections detail these patterns for each geographic location simulated.

East Tennessee

Simulated succession on upland oak-pine sites is strongly dominated by shortleaf pine, which reaches its greatest dominance over the first hundred years and subsequently is replaced by more shade-tolerant hardwoods. These sites support ≈160 T/ha of above-ground woody biomass. Under GISS and OSU scenarios the same qualitative pattern obtains, with only slightly less biomass (Figure 2). An important difference is that loblolly pine is the seral pine, virtually replacing shortleaf pine (Figure 3). This reflects the change in annual heat sums from ≈3600 to ≈5000 growing degree-days (refer again to Table 1). The more southern longleaf and slash pines are also common but never abundant (basal area of ≈1-4 m^2/ha). Hardwoods that succeed the pines include black gum, elm, and Shumard oak, all of which are indicative of more southern forest types.

Table 1. Median Growing Degree-day and Drought-day Indices for Four Study Sites, for Baseline and Three Climate Change Scenarios. Scenarios Are GISS, OSU, and GFDL $2xCO_2$. 90th Percentiles Are in Parentheses.

	Baseline	GISS	OSU	GFDL
Knoxville, Tennessee				
Degree-days	3616 (3809)	4917 (5130)	4845 (5060)	5327 (5542)
Drought-days	0.00 (0.23)	0.05 (0.33)	0.18 (0.39)	0.48 (0.52)
Florence, South Carolina				
Degree-days	4328 (4651)	5753 (6079)	5698 (6027)	6162 (6492)
Drought-days	0.00 (0.32)	0.13 (0.47)	0.22 (0.51)	0.52 (0.55)
Macon, Georgia				
Degree-days	4682 (4866)	6075 (6294)	6023 (6240)	6488 (6707)
Drought-days	0.09 (0.36)	0.33 (0.50)	0.43 (0.51)	0.54 (0.56)
Vicksburg, Mississippi				
Degree-days	4719 (4968)	6145 (6400)	6094 (6344)	6564 (6813)
Drought-days	0.14 (0.39)	0.35 (0.48)	0.41 (0.50)	0.51 (0.54)

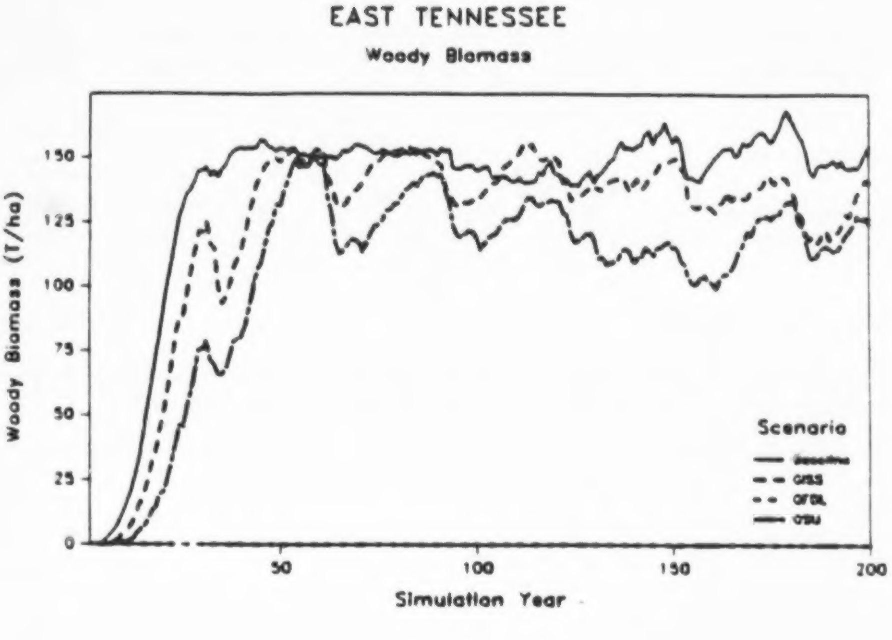


Figure 2. Trends in above-ground woody biomass in upland forests in east Tennessee, as simulated under current and $2xCO_2$ climate scenarios.

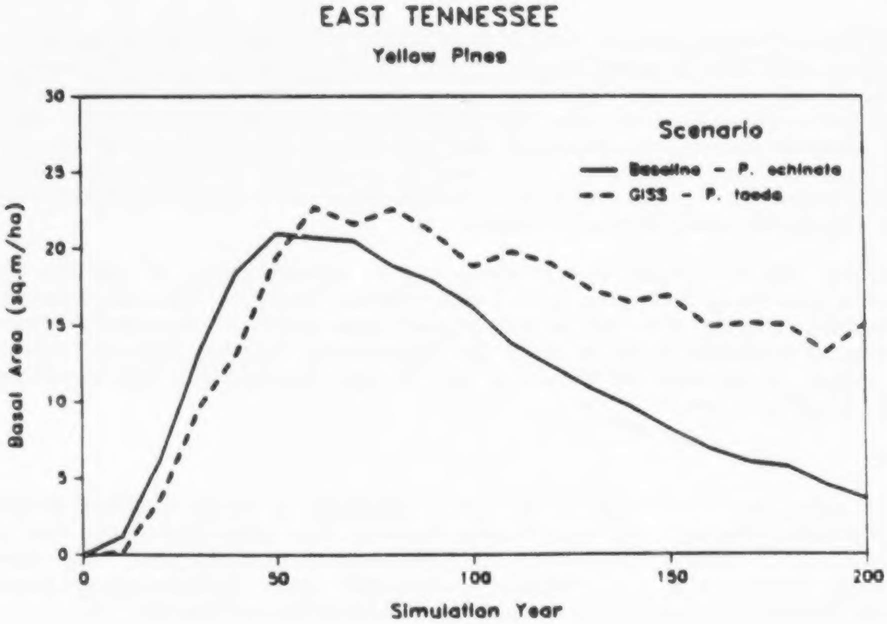


Figure 3. Basal area of dominant yellow pine in east Tennessee forests as simulated under current and GISS 2xCO_2 scenarios. Pine in baseline case is shortleaf; under GISS scenario, shortleaf is replaced by loblolly.

The GFDL scenario, which predicts the most severe warming and drying, resulted in no trees surviving in simulations, indicating that nonforest conditions (grassland or sparse savannah) would be favored.

South Carolina

Under the baseline climatic regime for the northern coastal plain, loblolly pine strongly dominates succession on upland sites, reaching a maximum of $\approx$25 m^2/ha in basal area at $\approx$60 years. Under the GISS scenario, loblolly pine is present but never common; longleaf pine is common but not dominant (maximum basal area $\approx$2 m^2/ha). Instead, mixed southern hardwoods occur even in the youngest seral stages; these include black gum, hackberry, laurel oak, and elm, all of which are associated with the more southern and western coastal plain. These forests as simulated under the GISS scenario support less than half the biomass of the baseline forest ($\approx$60 vs. $\approx$150 T/ha, Figure 4).

Both the OSU and GFDL scenarios predict thermal regimes at or beyond the domain of species tolerances (Table 1 and Appendix Table A.1). Marginal forests under the OSU scenario never reach more than 15 T/ha in biomass. No trees were supported under the GFDL scenario.

Georgia

Upland sites in Georgia, again, are strongly dominatd by loblolly pine during simulated succession. These forests support $\approx$150 T/ha of woody biomass. Under the most moderate of the climate-change scenarios (GISS), saplings of several southern coastal-plain species are established but none persist to develop a forest. The mix of species suggest that temperature was the predominant constraint on trees. Under the OSU regime, only xeric species are planted (post oak and blackjack oak), and these do not survive. These species suggest that drought became an operative constraint in this simulation, selecting only the most drought-tolerant trees from the southern species pool. The extreme GFDL scenario predicts drought and GDD indices beyond the domain of modeled species tolerances; no trees are planted.

Bottomland sites in Georgia were simulated with a moderate regime of saturated-soil conditions, corresponding to a spring flood duration of 1 month (mean $FD = 0.17$). This regime results in a forest dominated by black gum and sweetgum, with elms of nearly equal importance; these are key species of southern floodplain forests as described by Braun (1950). The climate-change scenarios predict responses very similar to those for upland sites, indicating that the temperature effects and late-summer drought are sufficiently extreme to override the effects of flood duration.

Mississippi

Like the other southern sites, upland succession in Mississippi is strongly dominated by loblolly pine in baseline simulations. This site is sufficiently droughty that even under present-day climate, more xeric soils can result in post oak savannahs instead of pinelands (simulations not included here). This reflects this site's position at the western margin of the deciduous forest biome. Under all climate-change scenarios, the site becomes too hot and dry to support trees as parameterized in the model (Table 1).

TRANSIENT RESPONSES TO CLIMATIC CHANGE

Transient scenarios were simulated by concatenating the 30-year weather data bases and applying the GISS Transient A conversions to yield 90-year transients. Two cases were simulated for each study site considered: a 90-year successional sequence from bare ground, and a 90-year projection of a 100-year-old stand (these were output from year 100 of the baseline simulations). In each case, the baseline simulations provide a control against which the transients can be compared (years 0-90 for the seral case; years 100-190 for the latter case).

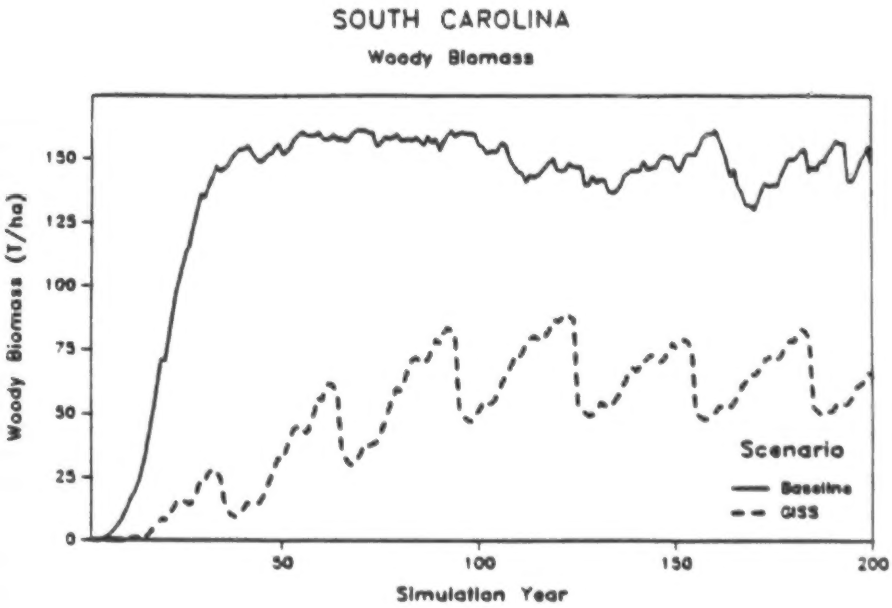


Figure 4. Trends in above-ground woody biomass in upland forests in South Carolina, as simulated under current and GISS $2xCO_2$ climate scenarios. OSU and GFDL scenarios did not support forest vegetation.

East Tennessee

The transient climate change for east Tennessee is evident in growing degree-days in ≈30 years, but becomes pronounced only after ≈60 years (Figure 5). Forest succession as simulated under this transient climate proceeds as with the control for ≈60 years, followed by a decrease in woody biomass (Figure 6a). This reflects a decline in the dominant species, shortleaf pine (Figure 6b). While these declines are appreciable after 90 years, the variability in both biomass and species importance is considerable (standard deviations are consistently 50-100% of means). This variability cautions against overinterpreting minor differences observed earlier in the simulations.

More mature forests subjected to the transient climate show a pronounced decline in biomass during years 60-70 of the simulation (Figure 7a). This decline corresponds to the sudden warming trend in that decade (refer again to Figure 5). The gap-phase mosaic nature of these more mature forests, reflecting the break-up and regeneration of the canopy, results the large variance in stand biomass observed in Figure 7a. Interestingly, the decline in biomass is not due simply to a parallel decline in the dominant species, shortleaf pine, but rather reflects a decline in several codominant and minor species. Shortleaf pine shows a general decline in the control as well as transient simulations, and the transient does not deviate appreciably from the control until after ≈80 years (Figure 7b). Loblolly pine, the species favored under the GISS 2xCO_2 scenario, does not appear in the transient forest until after 70 years, and at 90 years is still a relatively minor component of the forest (dashed line, Figure 7b).

South Carolina

The South Carolina transient climate is somewhat erratic, with several warming pulses recurring over the simulated years (Figure 8). Responses of seral forests reflect these pulses, especially in the later years of the simulation. This is evident at years 55 and 85 for woody biomass (Figure 9a) as well as the dominant loblolly pine (Figure 9b). In both cases, the first decline (at ≈55 years) is rather minor, while the later decline (at ≈80 years) is much more dramatic. These same two declines are also evident in simulations of more mature forest (Figures 10a&b). In these forests, the warming pulses at about years 55 and 80 are reflected in the baseline as well as the transient simulations; the transient cases do not deviate substantially from the baselines until after year 80.

Georgia

As with the east Tennessee case, the transient climate for the Georgia site shows a dramatic warming decade at ≈60 years into the simulation (Figure 11). This warming would roughly correspond to a 4-5° C. increase in mean annual temperature, which would be equivalent to the entire temperature change as projected over 90 years being telescoped into a single decade. Simulated responses of successional forests to this regime are obvious and intuitive: total biomass declines abruptly at year 60 (Figure 12a); the dominant species, loblolly pine, shows a similarly dramatic decline (Figure 12b).

More mature upland forests show the same qualitative pattern: a dramatic decrease in woody biomass (Figure 13a) and in the dominant pine (Figure 13b) at ≈60 years into the simulation. Recall that the GISS 2xCO_2 simulation for this site predicted marginal forest or nonforest vegetation, and the transient approaches this within the 90 simulated years. This reflects the dramatic warming of years 60-70 in the simulation.

Mississippi

The transient climate for the Mississippi site begins to deviate from the baseline within 20 years and shows a rather steady warming over the entire 90-year projection (Figure 14). As with the other study sites, there is a single decade that shows a pronounced warming, in this case, the sixth decade. Seral forests undergo dynamics similar to the baseline simulations for several decades, with a a slight and gradual reduction in woody biomass (Figure 15a) and the dominant species (Figure 15b). In each of these cases, a dramatic decline follows at about year 60, at which point the transient climate passes 6000 growing degree-days. Recall that this value is a critical value in the simulator, beyond which most modeled tree species succumb to heat stress (a similar point is passed

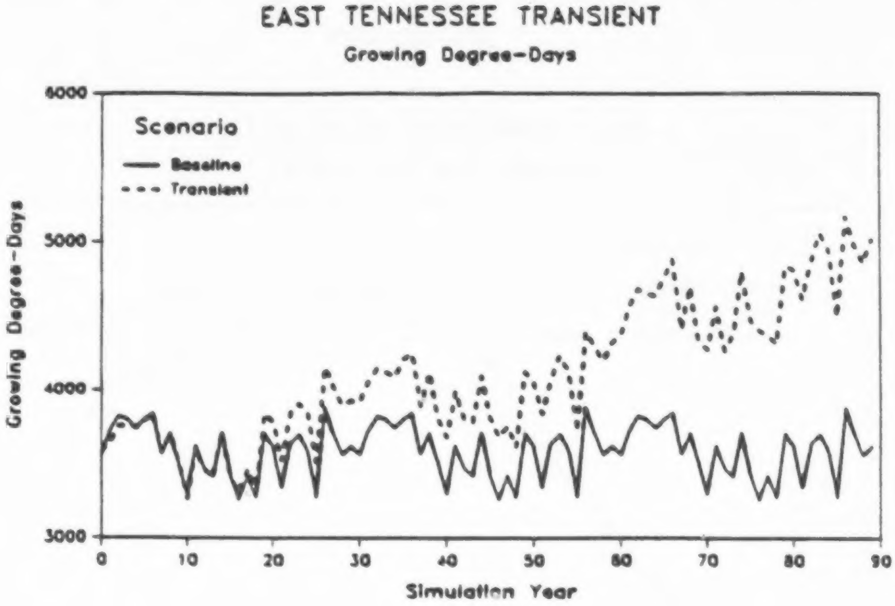


Figure 5. Transient climate, as annual heat sum, projected for east Tennessee (GISS transient A).

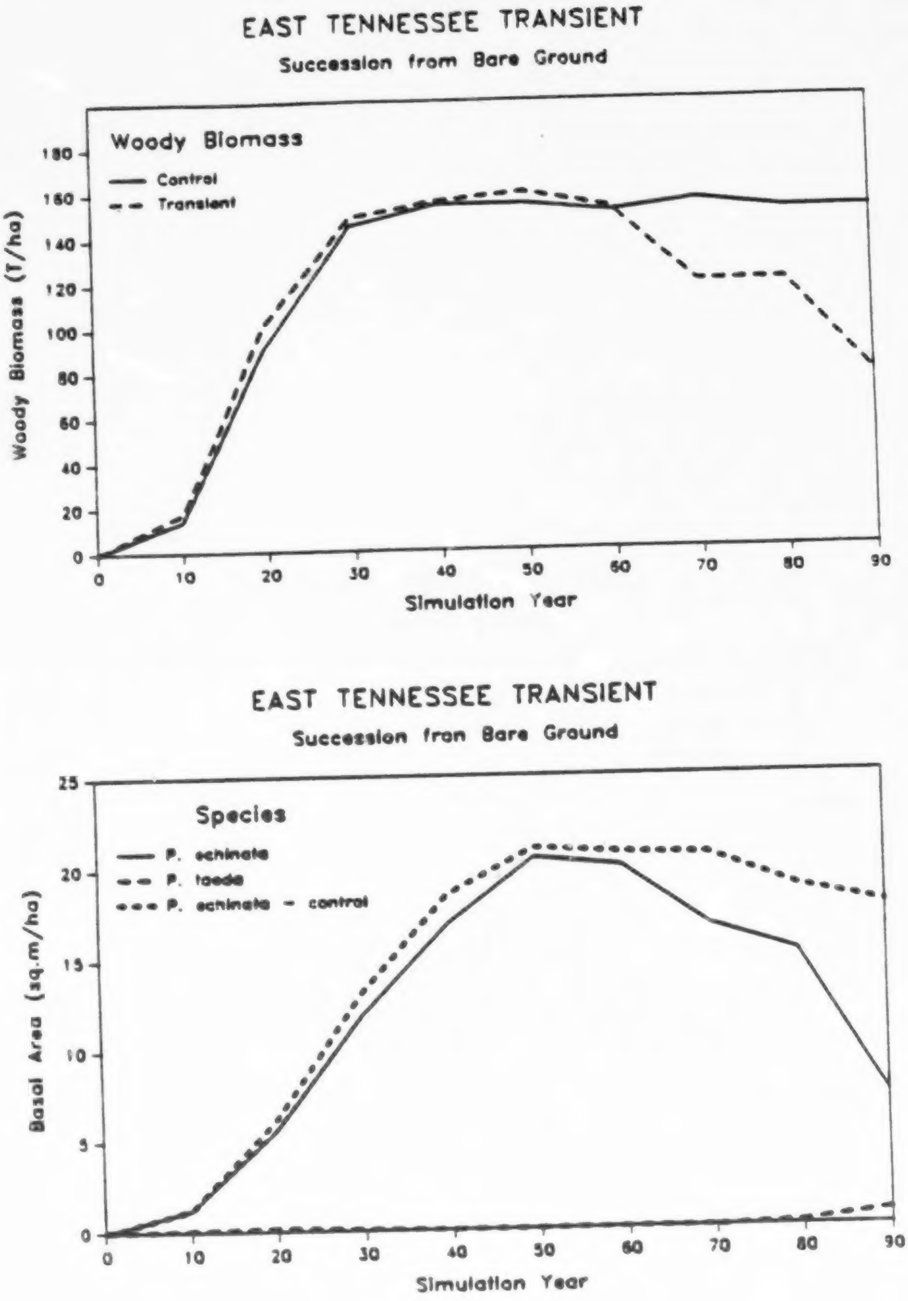


Figure 6. Simulated forest succession under transient climate in east Tennessee, as (a) woody biomass and (b) basal area of the dominant species, shortleaf pine.

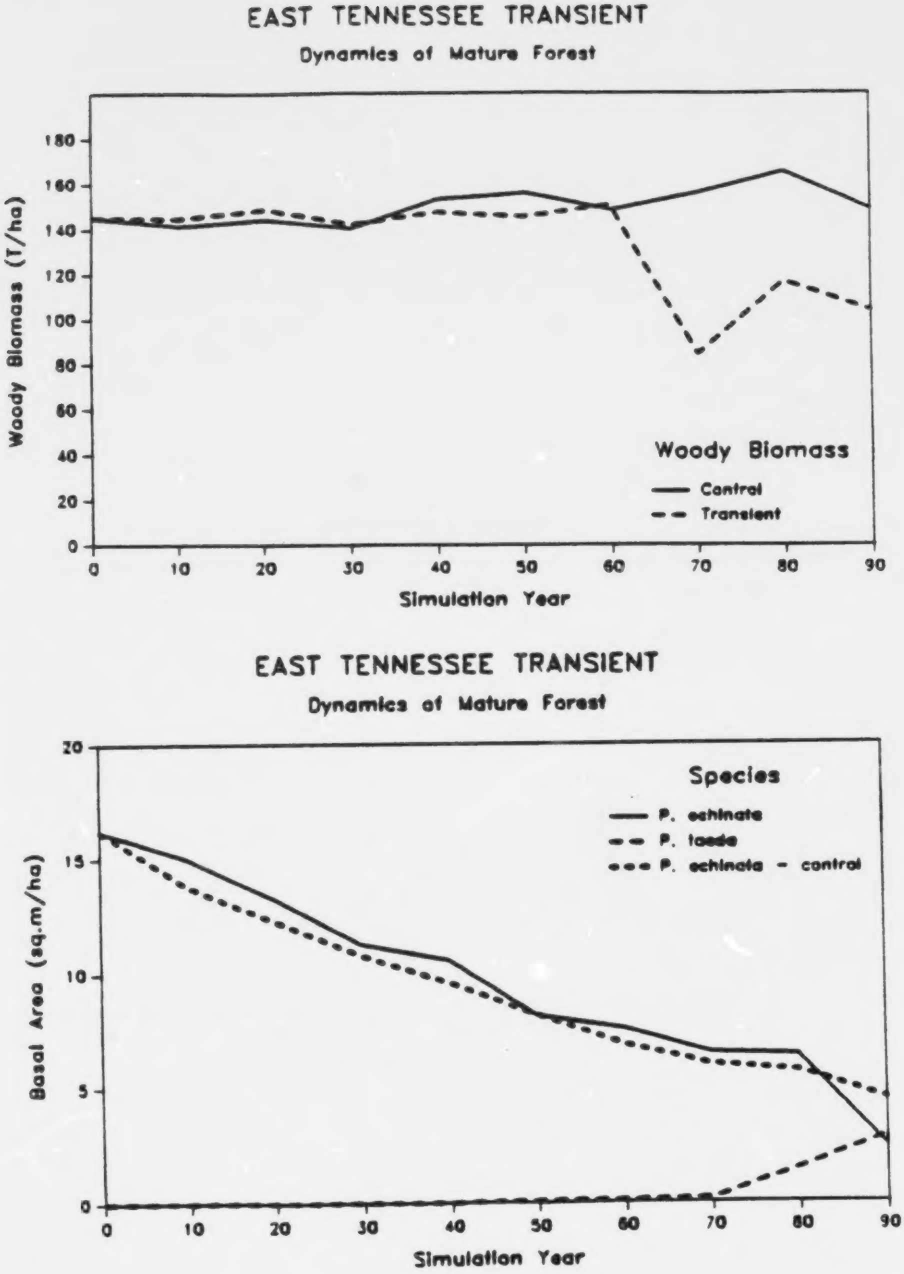


Figure 7. Simulated response of 100-year-old east Tennessee forests subjected to transient climate change, in terms of (a) woody biomass and (b) basal area of the dominant species, shortleaf pine.

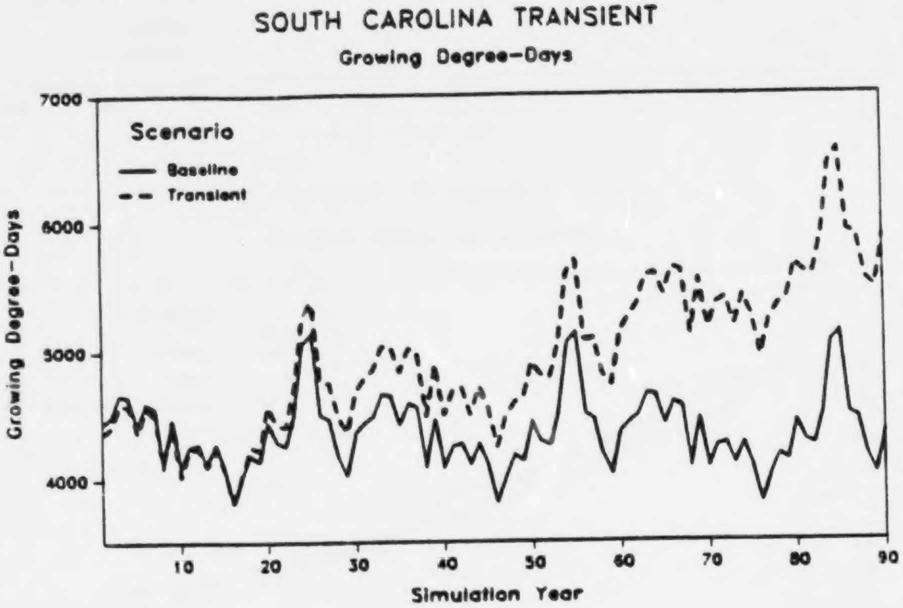


Figure 8. Transient climate, as annual heat sum, projected for South Carolina (GISS transient A).

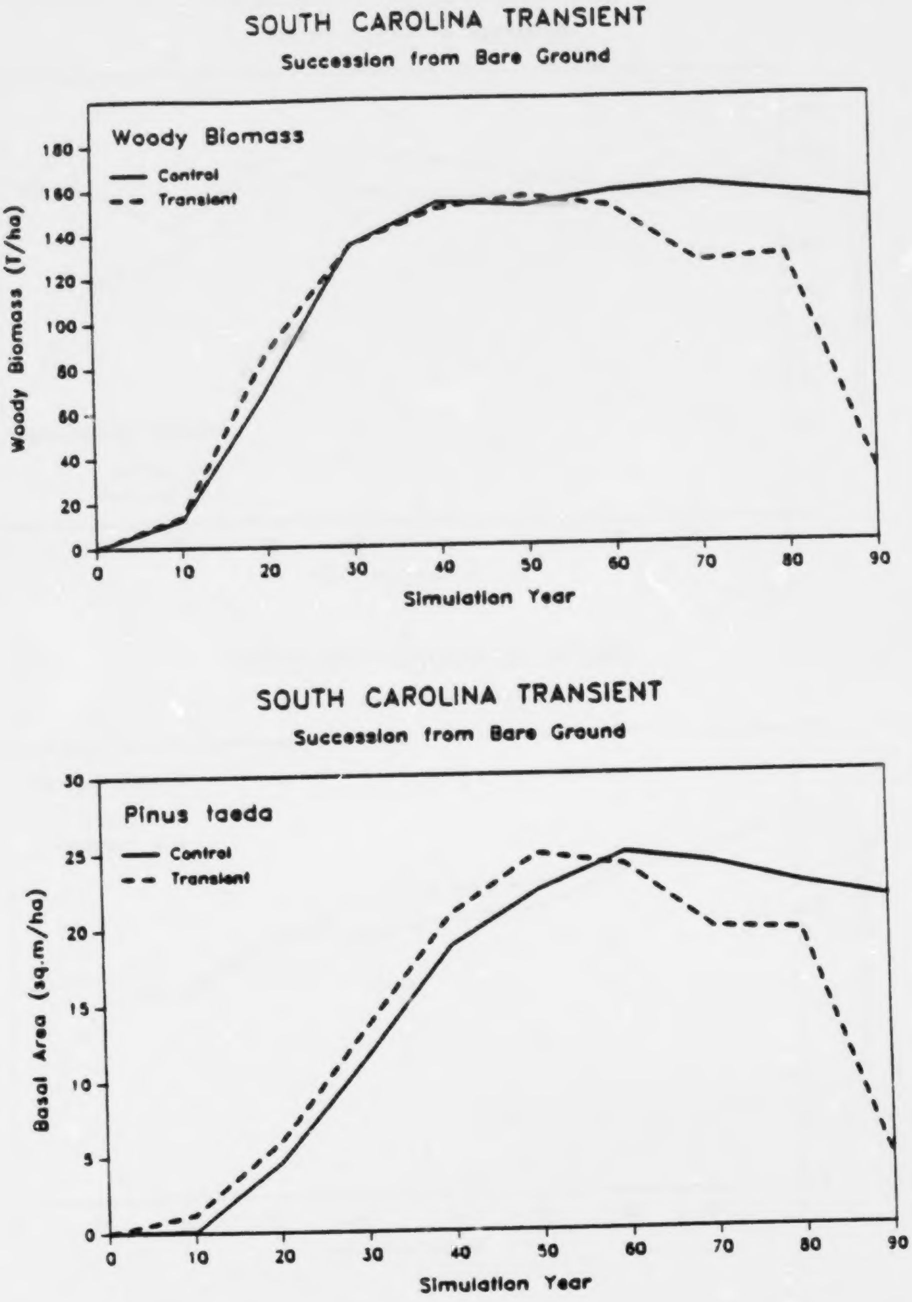
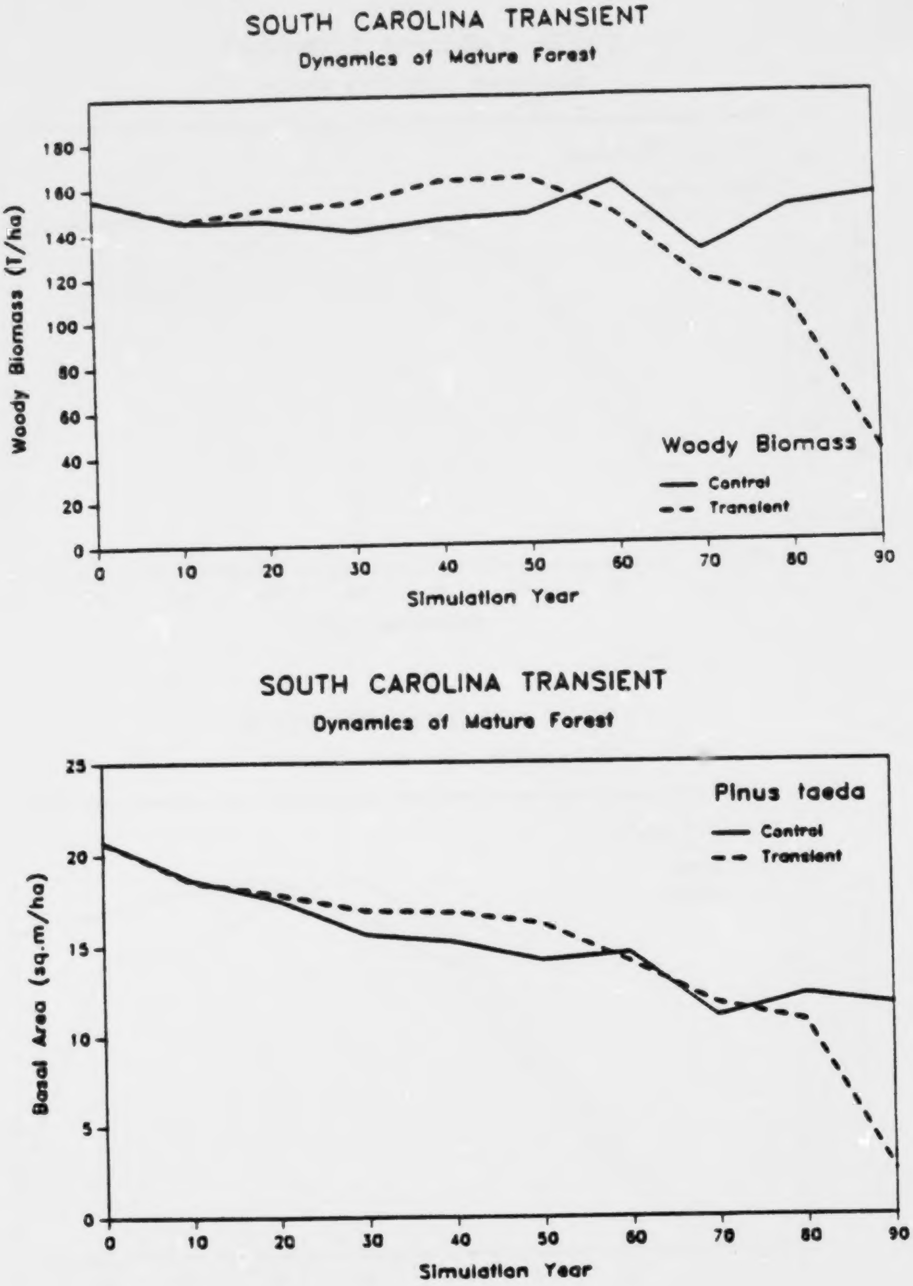


Figure 9. Responses of successional South Carolina forests to transient climate change, as (a) woody biomass and (b) basal area of loblolly pine.



SOUTH CAROLINA TRANSIENT

Dynamics of Mature Forest

SOUTH CAROLINA TRANSIENT

Dynamics of Mature Forest

Figure 10. Responses of South Carolina forests to transient climate change, for 100-year-old forests, (a) woody biomass and (b) basal area of loblolly pine.

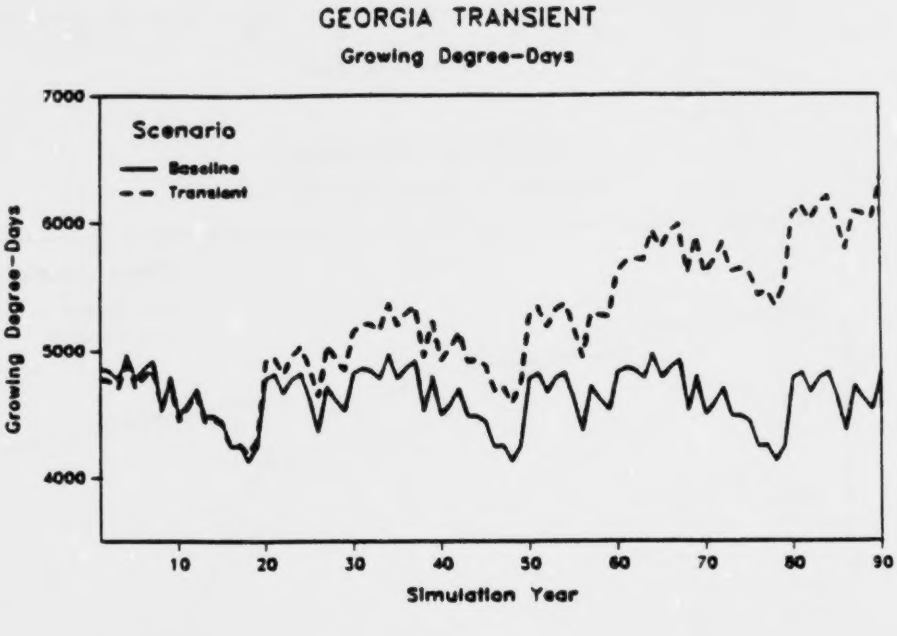


Figure 11. Transient climate, as annual heat sum, as projected for Georgia (GISS transient A).

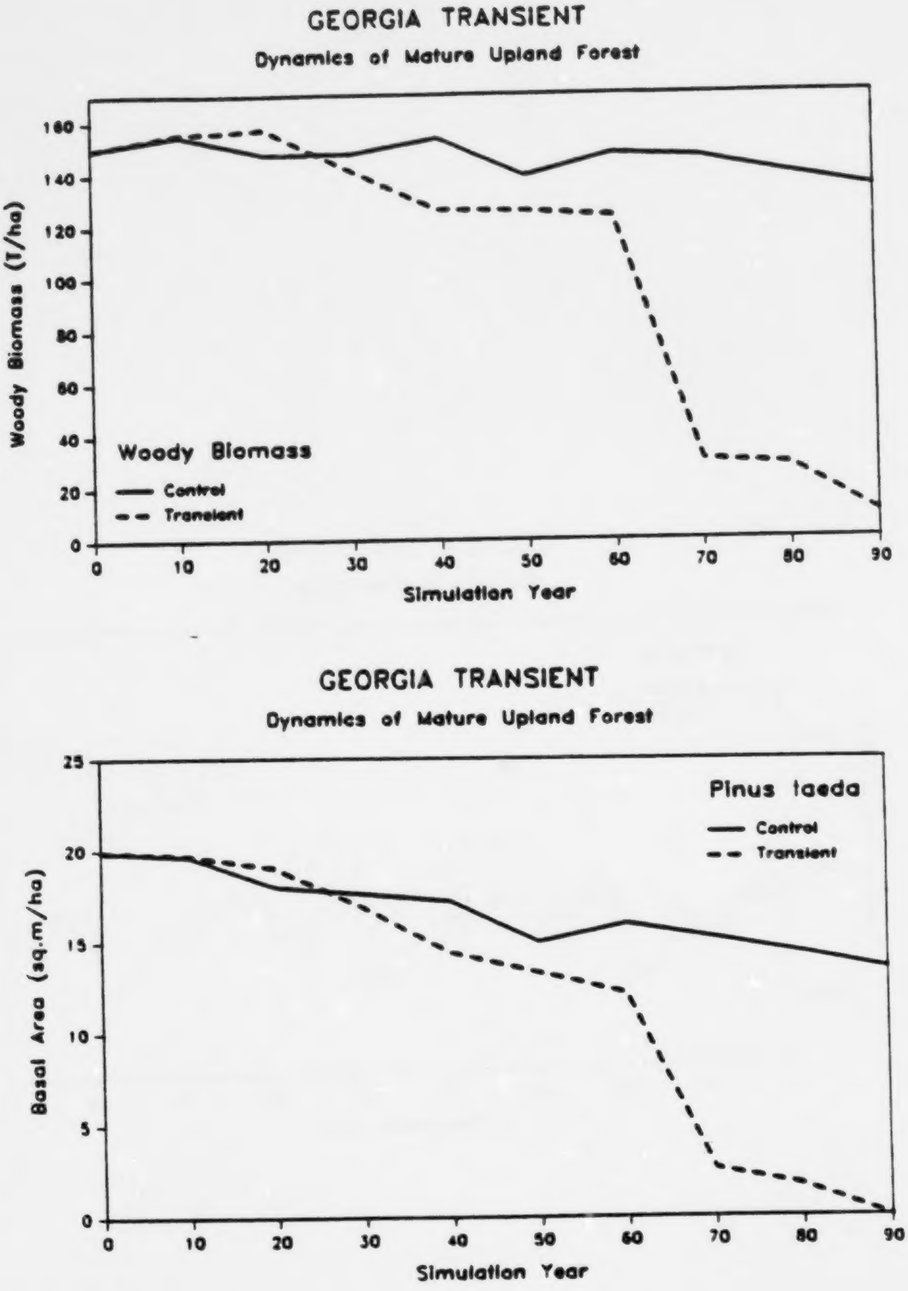
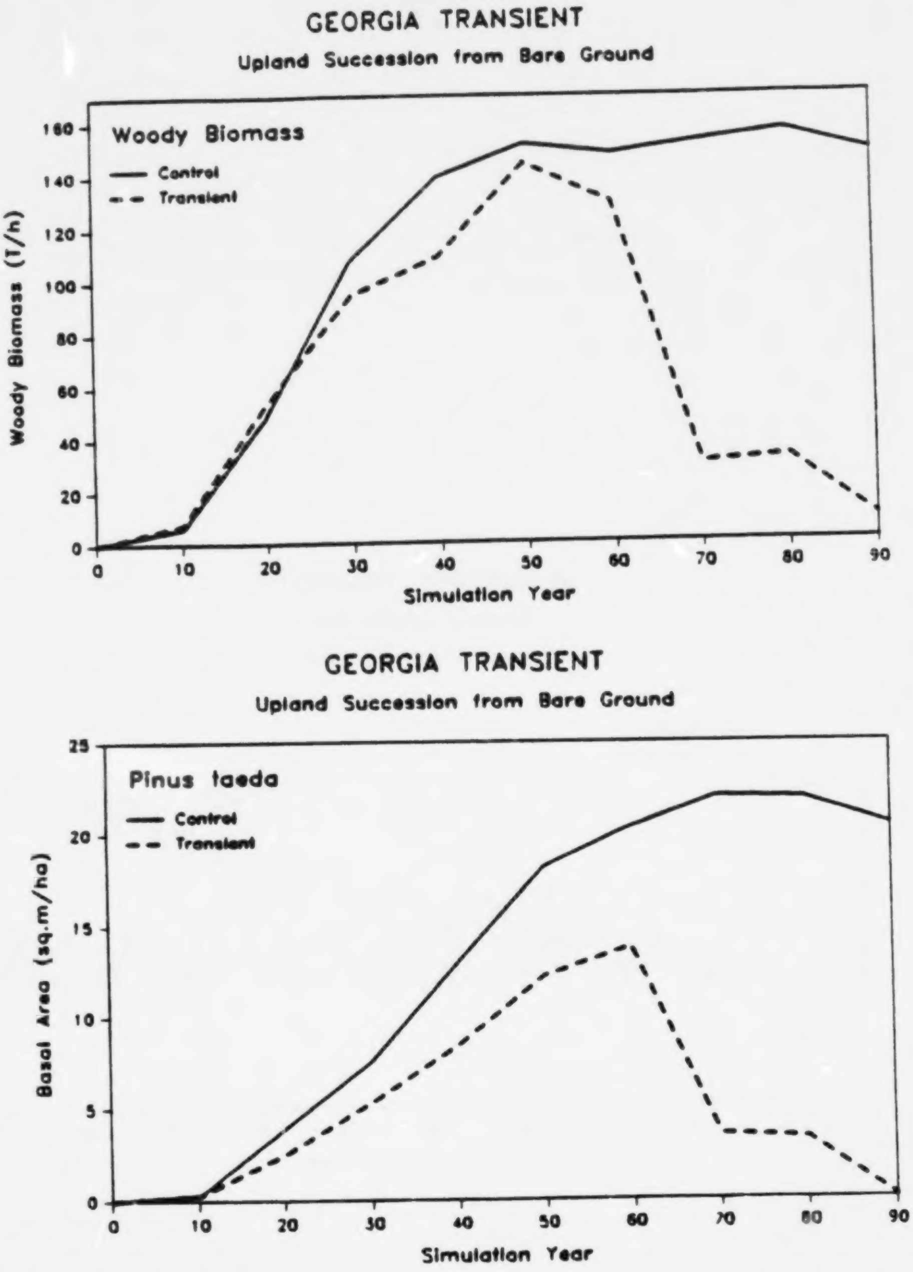


Figure 12. Responses of successional Georgia forests to transient climate change, as (a) woody biomass and (b) basal area of loblolly pine.



GEORGIA TRANSIENT

Upland Succession from Bare Ground

GEORGIA TRANSIENT

Upland Succession from Bare Ground

Figure 13. Responses of Georgia forests to transient climate change, for 100-year-old forests, (a) woody biomass and (b) basal area of loblolly pine.

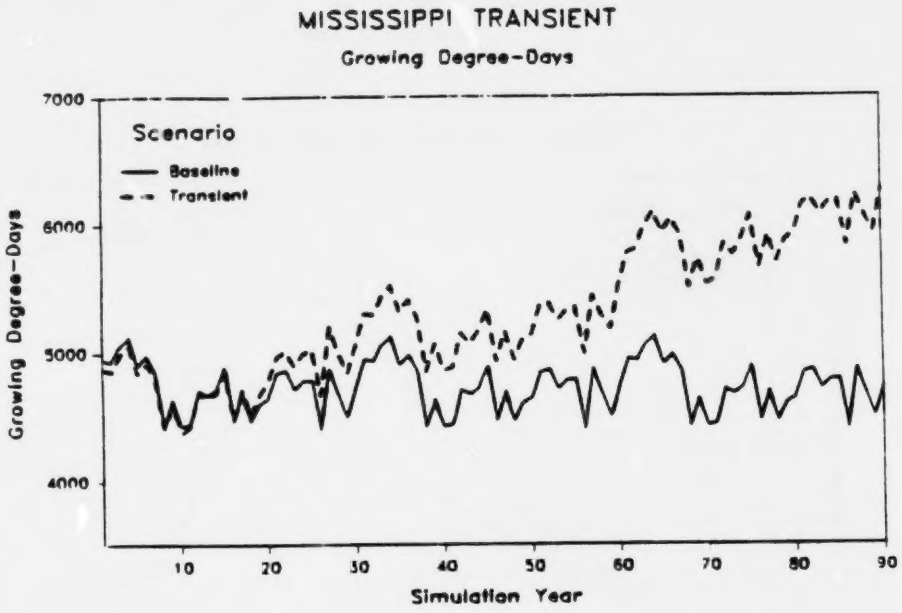


Figure 14. Transient climate, as annual heat sum, as projected for Mississippi (GISS transient A).

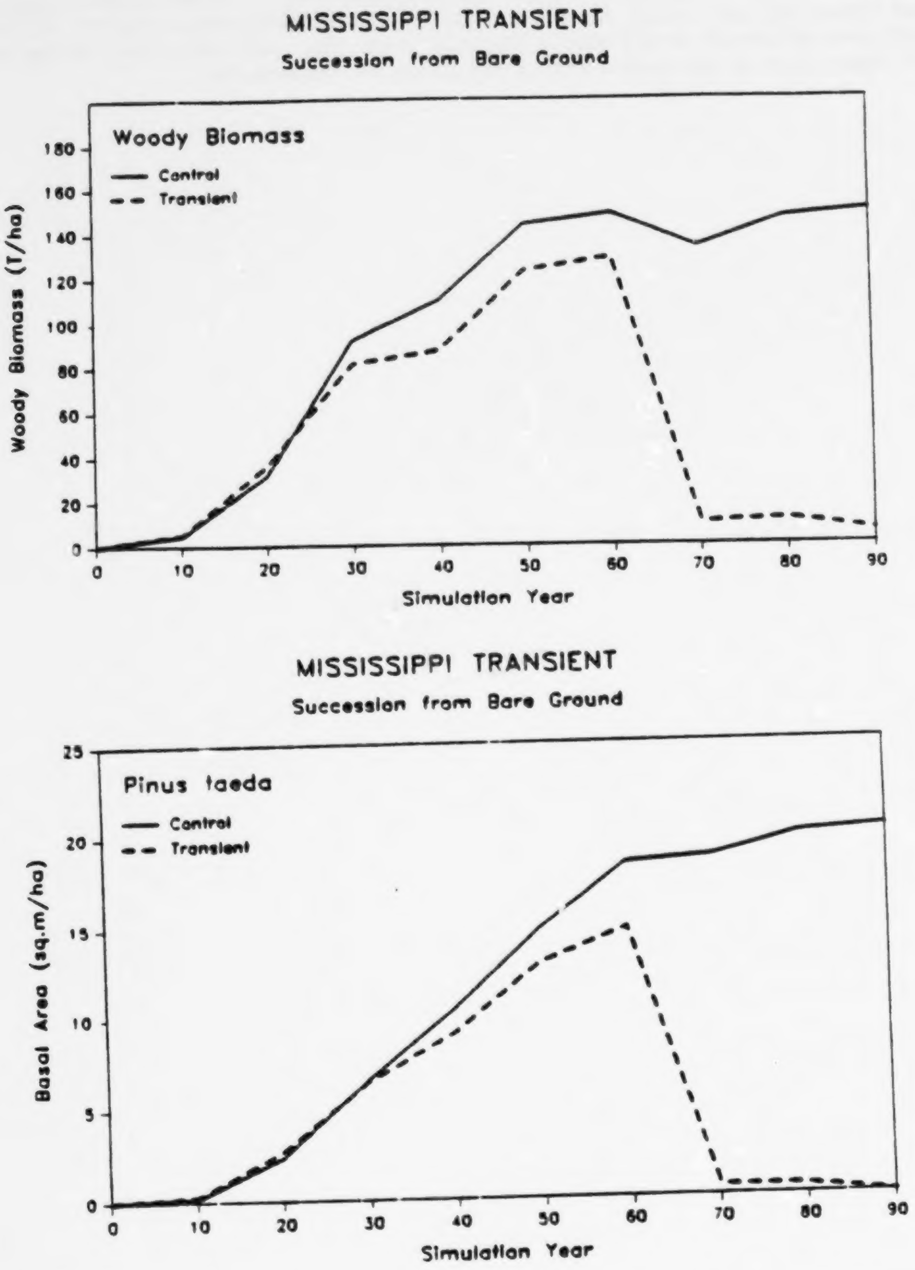


Figure 15. Responses of successional Mississippi forests to transient climate change, (a) woody biomass and (b) basal area of loblolly pine.

in the South Carolina transient at year 80; refer again to Figures 8-10). In the case of more mature forests, both biomass (Figure 16a) and loblolly pine (Figure 16b) show an appreciable decline before this critical point is reached; these declines are evident after as little as 40 years. This partly reflects the warming pulse at about year 30, which elicits an appreciable effect for this already hot and xeric site.

CHAPTER 4

INTERPRETATION AND DISCUSSION

In this discussion we interpret the simulation results, realistic as well as artifactual, to synthesize a general overview of how forests might respond to transient climate change. We begin with what we feel are realistic and robust model results, and then turn to aspects of the results that are less certain or compromised by lack of information. The aspects of transient forest reponses that are of interest here are the magnitude and timing of the response, because these attributes largely determine our ability to predict and detect such a response.

MAGNITUDE OF FOREST RESPONSE

Simulated forest change in response to the projected climate scenarios roughly corresponds to a northward migration of southeastern forest species. That is, the oak-pine forest types of east Tennessee are replaced by more southern elements (as indicated by loblolly pine). This prediction is consistent with results of Solomon et al. (1984), who used a similar model to project geographic implications of climate change. As previous studies have not utilized transient climates as predicted by GCMs, we emphasize these transients in this discussion.

In every case, the magnitude of predicted forest change is sufficiently dramatic as to make statistical comparisons of the long-term results superfluous. For the southern forests (sites in South Carolina, Georgia, and Mississippi), the prediction is that these forests will degrade to marginal forest or nonforest vegetation. This prediction represents the current state of our information base, and similar studies have reached similar conclusions (Solomon et al. 1984, Solomon 1986). But as we will argue, the basis for this prediction is somewhat uncertain (see following section on Model Uncertainties).

Of more immediate concern is whether forest change might be detectable in the near-term future, say 10-20 years. If so, then we could partially verify the model predictions, and would have more confidence in longer-term predictions of forest responses. In every case simulated, forest response to climate change is an initial decline in biomass reflecting a period of heavy stress mortality. Based on the degree of variability in the modeled forest dynamics, we must argue that we would likely have little power to discriminate such a decline from natural background variability in forest dynamics. Indeed, it seems that the alternatives would be to risk "crying wolf" by over-reacting to short-term fluctuations in forests triggered by natural variability in weather, or to be more conservative and ignore a real transient forest response until the change was well underway. Neither alternative is particularly appealing from a management standpoint.

TIMING OF FOREST RESPONSE

An important aspect of forest responses to transient climate change is evident in Figures 5-16, which should be emphasized again at this point. In every case, the forest decline is triggered by a rapid warming, a few stressful years in a row. The actual timing of these periods reflects the 30-year base weather traces used to generate the transient climate. In the South Carolina data, a warming pulse is obvious at about year 25 in the baseline (i.e., 1975); this pulse recurs at years 55 and 85 in the concatenated transient climate (Figure 8). Not surprisingly, the most dramatic forest declines correspond to these pulses.

The South Carolina case is particularly obvious, but the same behavior is evident for the other study sites. Indeed, much of this behavior can be attributed to the shape of the transient climate predicted by the GISS model. The transient, which was provided to EPA as smoothed (time-averaged) conversion ratios comparing the transient data to GISS-generated baseline conditions under current CO_2, shows a nonlinear trend with rather abrupt changes around years 30 and 60 (Figure 17). These pulses coincide with the pulsed diebacks in the modeled forests. Thus, the transient forest responses are partly artifactual, a consequence of the GISS-modeled transient as modified by baseline weather records for each study site.

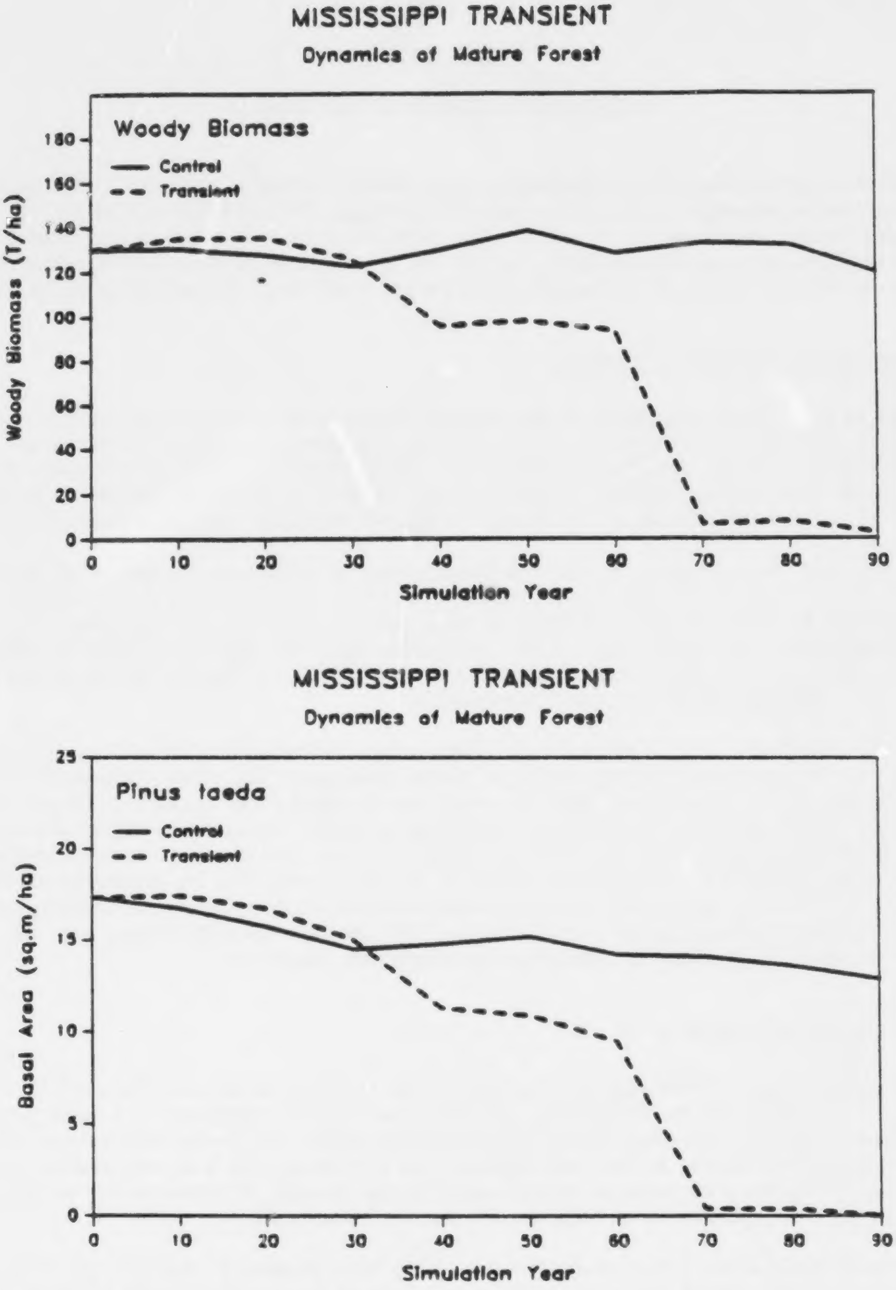


Figure 16. Responses of 100-year-old Mississippi forests to transient climate change, as (a) woody biomass and (b) basal area of loblolly pine.

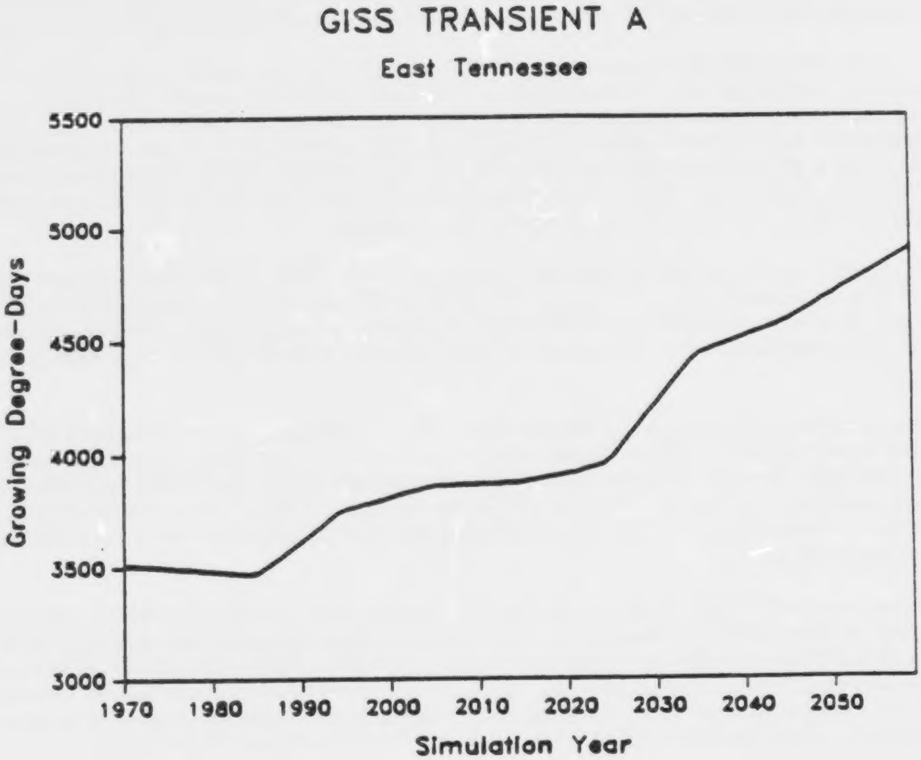


Figure 17. Growing degree-day transient as predicted by GISS transient A scenario. Plotted values are 30-year mean monthly temperatures multiplied each year by conversion ratios for east Tennessee site, yielding a transient unmodified by interannual variability in the baseline data.

Yet this pulsed behavior in the modeled forests is a realistic attribute of forests. In real forests, we would expect weather anomalies to modulate forest dynamics, with particularly stressful periods resulting in episodes of heavy mortality. In the context of predicting forest response to climate change, the implication is that we might expect an appreciable forest decline at some time over the next several decades, but the exact timing of such a decline, as well as the rate or abruptness of the decline, would depend on actual weather patterns. Thus, we might expect a forest response perhaps 40-70 years from now, but we cannot hope to predict the exact timing of the response.

Confounding Factors

Forest responses to climatic variability may be confounded by a number of other factors. Among these are stand age, and the ameliorating or exacerbating effects of other environmental factors. Forest sensitivity to environmental stress increases with stand age, because older trees are more vulnerable to stress. This reflects the high maintenance costs of large trees, which leaves little margin for a reduction in photosynthate production. Thus, we would expect very mature trees to show the effects of climate change sooner than young trees.

Other environmental factors surely contribute to observed patterns of forest growth, mortality, and regeneration. Additional stresses would have a synergistic effect with climatic (heat and drought) stress, resulting in increased local mortality at such sites. Thus, there is a sense in which already stressful environments (very xeric sites; harsh microenvironments) present themselves as likely points to monitor for the appearance of episodic or unusually heavy mortality that might indicate environmental change. Unfortunately, because "stress" is so difficult to diagnose specifically, it seems that real difficulties could arise in any effort to ascribe observed mortality to a single environmental factor (here, climate change).

We should note that not all environmental change is for the worse. It has been suggested that one direct effect of CO_2 enrichment may be to increase the water-use efficiency of plants (Strain and Cure 1985). If this is the case, then forest response to possible drying (through higher temperatures, lower precipitation, or both) might be somewhat ameliorated as compared to simulations based on our current estimation of trees' drought tolerances.

Pastor and Post (1988) have noted that positive feedbacks between soil water content and available nitrogen may make forest response to climate change more complex than intuition might suggest. Their model illustrated two possible trajectories for northern forests under a warming climate: on mesic soils with sufficient soil water, increased decomposition rates led to higher nitrogen availability and greater forest productivity; on drier soils, drought stress reduced forest productivity. We do not know at what soil moisture level this bifurcation in system behavior might occur.

Several natural disturbances may be mediated by climate, either directly or indirectly. For example, fires would be more likely under a warming and drying climate, because of greater fuel loads and higher chances of ignition. It is difficult to predict the degree to which this might affect southeastern forests, as fire regimes would likely be contolled through management (e.g., supression). Pest outbreaks could also be affected by climate change, for example, in cases where the geographic range of a pest organism is currently bounded by winter temperatures. Again, predictions about these factors are beyond the scope of this report.

MODEL UNCERTAINTIES AND CAVEATS

There are two sorts of uncertainties in simulation studies such as this. The first sort concerns conceptual questions about operative mechanisms in forest response to environmental drivers. The second problem arises when the mechanisms are thought to be understood, but implementation is limited by a lack of data of sufficient precision or resolution. The former problem appears as underspecified (or incorrectly specified) algorithms in the model, while the latter problem translates into problems in parameter estimation. Both sorts of problems are inherent in this study.

One parametric problem to which we previously alluded concerns the estimation of maximum tolerable heat sums for southern tree species. As noted, southeastern forest species do not occur under regimes of more than ≈6000 growing degree-days, a value that occurs in north-central Florida (the Gulf coast has an annual heat sum of ≈5500 GDD). In the simulator, most southern tree species thus have their thermal maxima artificially bounded. These species do not occur under warmer regimes because (a) they are bounded by water, (b) they are bounded by tropical or coastal evergreen forest elements, and/or (c) they are bounded to the southwest (in Texas and Mexico) by drought. In each case it is not possible to specify what the actual maximum tolerable heat sum might be for these species. Thus, the model will not simulate forests under regimes of more than ≈6000 GDD, but in fact this may be an artifactually low boundary condition. Paleo-ecological records offer no additional insights, as there is no record of forest (pollen) distributions under climates warmer than those projected over the next several decades (Delcourt and Delcourt 1987). We have no means of correcting this source of uncertainty.

A second source of uncertainty in the model concerns the implementation of stress tolerance and stress mortality. In the model, a tree subjected to an environmental condition near its specified tolerance suffers reduced growth; more extreme conditions result in no growth. Stressed individuals (showing less than minimal growth) are subjected to a fixed, elevated mortality rate (see details in Appendix). This implementation does not incorporate myriad physiological or morphological adaptations to environmental stress (see Turner and Kramer 1980). A more detailed implementation of stress responses in trees is beyond the scope of this study, hence, represents another source of uncertainty in our results.

Proximate Mechanisms in Species Response to Climate

It seems obvious that a more fundamental understanding of the mechanisms that affect tree response to climate will be crucial. Solomon et al. (1984) discussed various proximate mechanisms that might be interpreted as forest response to "climate" in a general sense. These mechanisms include direct weather effects as well as indirect effects mediated by climate (e.g., insect or pest outbreaks, or disturbances such as fires and floods). Moreover, trees are more or less susceptible to these factors depending on their age or size: flowers may be sensitive to spring frosts, while seedlings are vulnerable to late-summer drought, and mature trees may succumb to multiple droughts over a few years. All of these factors may be intercorrelated and interpreted as "climate." Our current model implementations reflect our current understanding, and simplify the richness and complexity of forest response to these many proximate mechanisms. Thus, our model-based predictions about forest responses to climatic variability are limited by a lack of direct evidence detailing the proximate mechanisms of this response.

We must emphasize that our current empirical understanding of forest response to climatic variability is sufficiently lacking that grandiose predictions about climate-change scenarios are probably premature. This study underscores the need for a great deal of basic research into the mechanisms by which trees and forests respond to climatic variability in general, and specifically, to identify the proximate climate factors and biological mechanisms that govern such responses.

Seed Availability and Species Migration

Perhaps the most critical uncertainty in this study concerns seed availability and rates of species migration. In the model, this translates into the implicit assumption of which species are available for establishment in any given year. This study follows Botkin (this volume) in generously assuming that any species in the regional pool is available throughout the simulation. Thus, under a changing climate in east Tennessee, more southern species were allowed to enter the modeled forest. This implementation ignores constraints on seed sources and seed dispersal. This is an extremely critical assumption in the context of this study, because this assumption dictates very different forest responses to climate change.

If one assumes that any species in the regional (southern) species pool is available in forest simulations, then more southern species enter east Tennessee forests when the climate becomes too warm for the local species. The result is that species replacement occurs (e.g., loblolly pine for shortleaf pine, Figure 3), which mitigates the decline in forests due to stress mortality. Although we had no basis for including an alternative species pool for the more southern study sites, it is reasonable to suggest that a similar replacement might occur on these sites if species migration rates were sufficiently fast relative to climate change. Note that species replacement does not imply that no forest decline will occur. Declines evident in the east Tennessee transient simulations (Figures 6-7) reflect heavy mortality under stress. The magnitude of this mortality would likely depend on the magnitude and suddenness of climate change. The degree to which species replacement might mitigate this episodic mortality would depend on how well the replacement species might be adapted to the new climate, and how rapidly such replacement might occur.

Alternatively, if southern species are assumed not to be available, then local stress mortality would go unanswered by species replacement. A dramatic forest decline would result, even in areas for which well-adapted species exist, if these species were not locally available. Current estimates of tree species migration rates, inferred from Holocene pollen records (Davis 1981, Delcourt and Delcourt 1987), suggest maximum rates on the order of 50-100 m/yr. These rates are nearly an order of magnitude too slow to track a transient climate as projected for the next several decades. If climate change is sufficiently rapid and extreme to initiate widespread and synchronous stress mortality, then we must conclude that much of this mortality would be unmitigated by species replacement.

As a perhaps more realistic intermediate case, some individuals of species better adapted to the changing climate would probably be locally available, and these would provide at least a small source pool of propagules. In this case, the magnitude of local forest decline would be determined in part by the richness of the local species pool (the availability of alternative, better adapted species). The duration of the decline would be determined by the rate at which appropriate species could migrate into the area or by the rate at which local individuals could mature to provide an adequate seed source.

In a management context, many effects of seed availability might be mitigated by planting species appropriate to the changing climate. The practice of planting seeds from carefully selected genetic stock or provenances is well established in silviculture. This could perhaps be extended as necessary, such as to provide tropical or southwestern species for particular sites, as climate projections indicated. Again, careful research would be required to identify appropriate provenances.

CHAPTER 5

IMPLICATIONS

Results of this study are in agreement with previous studies in suggesting that projected climate changes will initiate a northward migration of forest species, with current geographic distributions displaced distances on the order of hundreds of kilometers. Simulations suggest that some southeastern sites would become too xeric to support well-developed forest, and instead would be replaced by some other vegetation type (savannah, grassland, or scrub). Because of the peculiar biogeographic context of these areas (the Gulf influence, the proximity of the southern hemisphere flora, and the xeric boundary represented by south Texas and Mexico), it is not possible to predict the fate of these southeastern sites.

Transient responses of simulated forests are characterized by dieback episodes corresponding to pulses of rapid climate change. Actual forest response would depend on the magnitude and timing of such warming pulses. Both of these aspects of transient climate change are subject to some uncertainty in terms of prediction or detection.

This study is compromised by uncertainties about species responses to proximate environmental factors, and about actual mechanisms and adaptations for stress tolerance. Perhaps the most critical uncertainties concern seed availability and rates of species migration. The extent to which species replacement can mitigate synchronous stress mortality due to climate change is a principal factor determining the magnitude and duration of forest decline under a changing climate. The highest research priority should be placed on resolving these uncertainties.

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APPENDIX

DOCUMENTATION OF THE FOREST SIMULATION MODEL

This appendix summarizes the implementation of the ZELIG forest simulator. The emphasis is on those details of the model that are pertinent to this particular application, especially the environmental constraints affected by climate. This section also overviews model demographics, statistical concerns with replication, and notes on parameterization.

Gap-scale Constraints

The implementation of shading effects retains the original FORET approach of modeling light extinction through a forest canopy as a negative-exponential decay following Beer's Law (Shugart 1984):

$$Q_h = Q_0\exp[-kL(h')], \qquad (1)$$

where Q_h is the light available at height h, Q_0 is incident light, and L(h') is cumulative leaf area (m^2/m^2) above height h. Here, k is a constant describing light extinction through the canopy; this constant is related to leaf angle, branching geometry, and the absorption properties of leaf tissue, and for deciduous forest canopies takes on values on the order of 0.25- 0.50 (Monteith 1973). If Q_0 equals 1.0, this decay defines the proportion of full sunlight available at a given height of the foliage profile. Species response to available light was originally described for 2 shade-tolerance classes (Botkin et al. 1972), using equations of the form:

$$r(Q_h) = c_1(1.0-\exp[c_2(Q_h-c_3)]), \qquad (2)$$

where Q_h is as described above, c_1 is a scaling constant, c_2 determines the rate of change in growth relative to change in sunlight (i.e., steepness of the response curve), and c_3 is the compensation point (where net growth is 0). ZELIG uses 5 shade-tolerance classes (Baker 1949, Fowells 1965); these functional forms are evenly interpolated between the 2 shade-response functions originally implemented in FORET (Figure 1).

Temperature effects on tree growth are simulated as a function of an annual heat sum, with growing degree-days tallied from a 5.56°C. base. This implementation reflects empirical correlations between species distributions and annual heat sums, as observed at a coarse (e.g., continental) scale of resolution. ZELIG retains the original convention of modeling species response to growing degree-days as a parabolic function (Botkin et al. 1972, Shugart 1984):

$$r(GDD) = \frac{4.0*(GDD_{max}-GDD)(GDD-GDD_{min})}{(GDD_{max}-GDD_{min})^2}, \qquad (3)$$

where GDD is growing degree-days, subscripted to denote the maximum and minimum values observed over the present-day distribution of a species (Figure 2).

The soil moisture routine in ZELIG calculates a monthly water balance for each soil type, which is summarized as the percentage of days during the growing season for which there is inadequate soil moisture

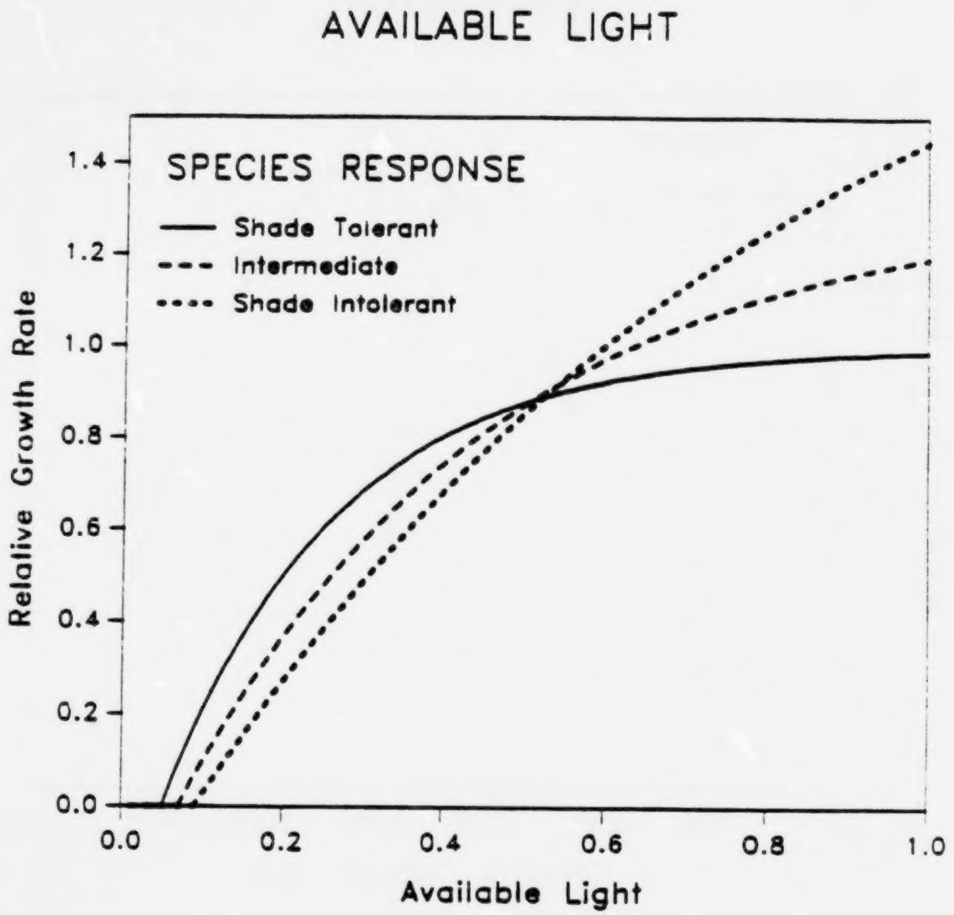

Figure A.1. Multiplier used to adjust tree growth rate in response to available light.

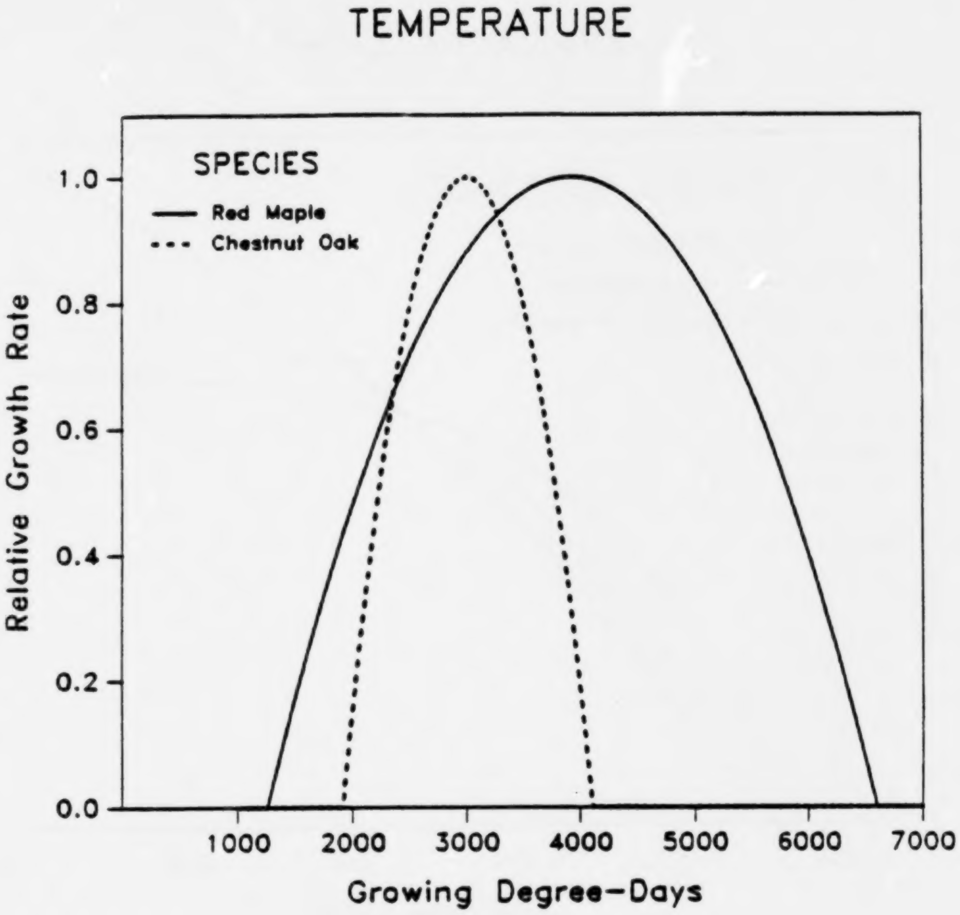

Figure A.2. Multiplier used to adjust tree growth rate in response to temperature as annual heat sum.

(soil moisture below wilting point). This routine is based on the method of Thorthwaite and Mather (1957) as modified by Pastor and Post (1984, 1985). Because basal area growth has been shown to decrease linearly with moisture stress (Bassett 1964), and basal area is a square function of diameter, species response to drought stress (as relative diameter increment) is modeled as a square-root function. This function relates the percentage of drought days in the year to a species-specific maximum sustainable percentage of drought days (Pastor and Post 1985):

$$r(D) = \sqrt{}(D^{*}-D)/D^{*} \qquad (4)$$

where D is the percentage of drought days during the growing season and D^{*} is the maximum tolerable percentage for a given species (Figure 3).

To simulate bottomland forests, a new constraint has been incorporated into ZELIG to account for high water table or flood conditions. This implementation is simplistic in assuming only that (1) a flooding regime or depth to water table is so dependent on local topography and drainage characteristics that it is reasonable to postulate a high-water regime that is largely independent of soil conditions and regional weather; and (2) relative to the mean high-water regime, conditions in any given year are loosely correlated with springtime water balance (years with dry springs will have a lower water table, and vice versa). Thus, a bottomland site in ZELIG has a declared mean value for a parameter flood duration (FD), which is defined to be the proportion of the growing season during which the soil is saturated. FD is linearly related to annual springtime water deficit (deviation from mean PET for March-April-May). Because this relationship is rather weak in empirical studies ($r^2 \approx 0.6$, D. Hains, pers. comm.), stochastic noise is added to the predicted value for FD. Species response to FD is modeled similarly to the soil moisture response, as a square-root function of the maximum tolerable FD for each species. Species tolerances were parameterized as classified by Teskey and Hinckley (1977).

Differential species response to soil fertility is modeled by specifying a nutrient-response category for each species. Species tolerant to nutrient stress grow adequately on poor soils and do not respond substantially to fertilization (or rich sites), while intolerant species fare badly on poor sites but are very responsive to enriched soils; a third class is intermediate in response (Mitchell and Chandler 1939). Three previous gap models (Aber et al. 1979, Weinstein et al. 1982, Pastor and Post 1985) have used the empirical results of Mitchell and Chandler (1939) to derive polynomial functions relating relative tree growth to nutrient availability. In ZELIG, these functions are doubly relativized so that both growth rate and soil fertility vary between 0.0 and 1.0:

$$r(F) = c_1 + c_2F - c_3F^2, \qquad (5)$$

where the c's are regressed constants. Here, soil fertility (F) is defined relative to the best possible site, and tree growth is retarded on soils of lesser productivity (Figure 4). Note that ZELIG does not model the dynamics of nutrient availability; relative soil fertility is a parameter provided as input data.

The functional forms of each of these constraints provide dimensionless multipliers on the interval [0,1] (they are truncated to 0.0 or 1.0 if they go out of bounds). ZELIG uses an interaction between below-ground and above-ground constraints to modify potential regeneration and growth of trees. The below-ground constraint is chosen as the minimum of the soil fertility and soil moisture multipliers, an approach that assumes that water-use efficiency and nutrient uptake are so inter-related that it would be inappropriate to treat them independently. The above-ground constraint of available light is multiplied by the below-ground constraint, an interaction that reflects the empirical observation that photosynthetic efficiency decreases with moisture stress (Chapin et al. 1987).

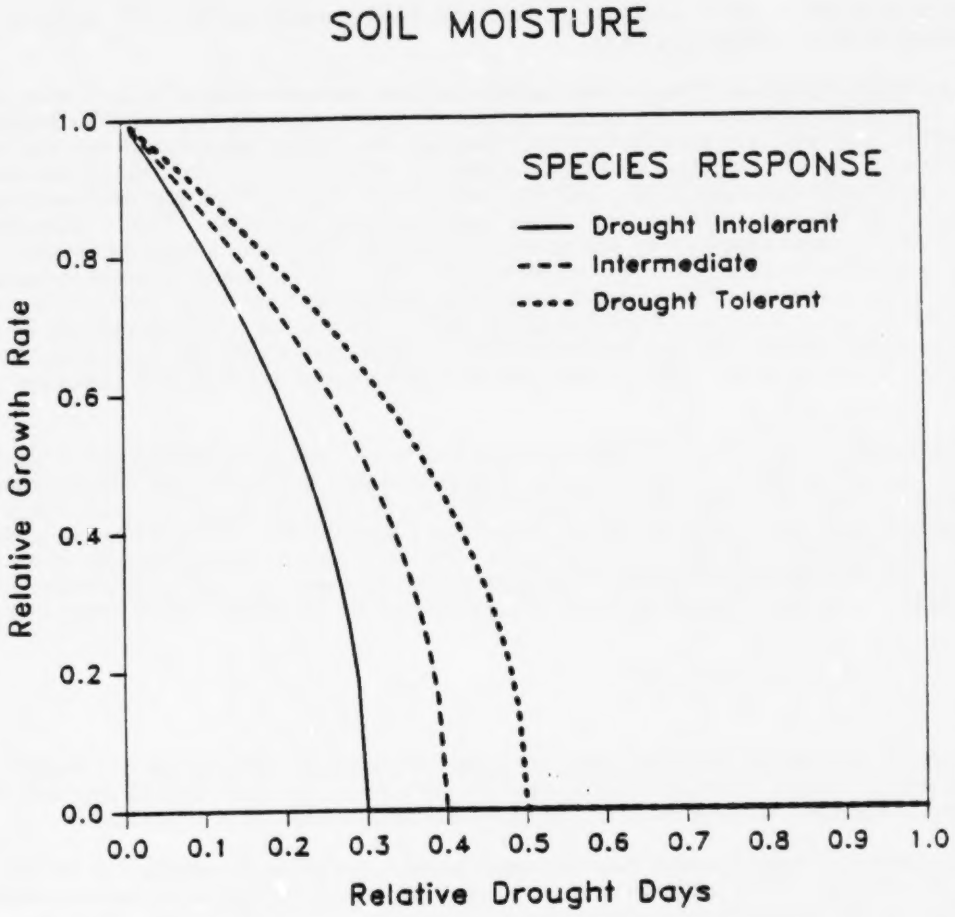

Figure A.3. Multiplier used to adjust tree growth rate in response to moisture stress.

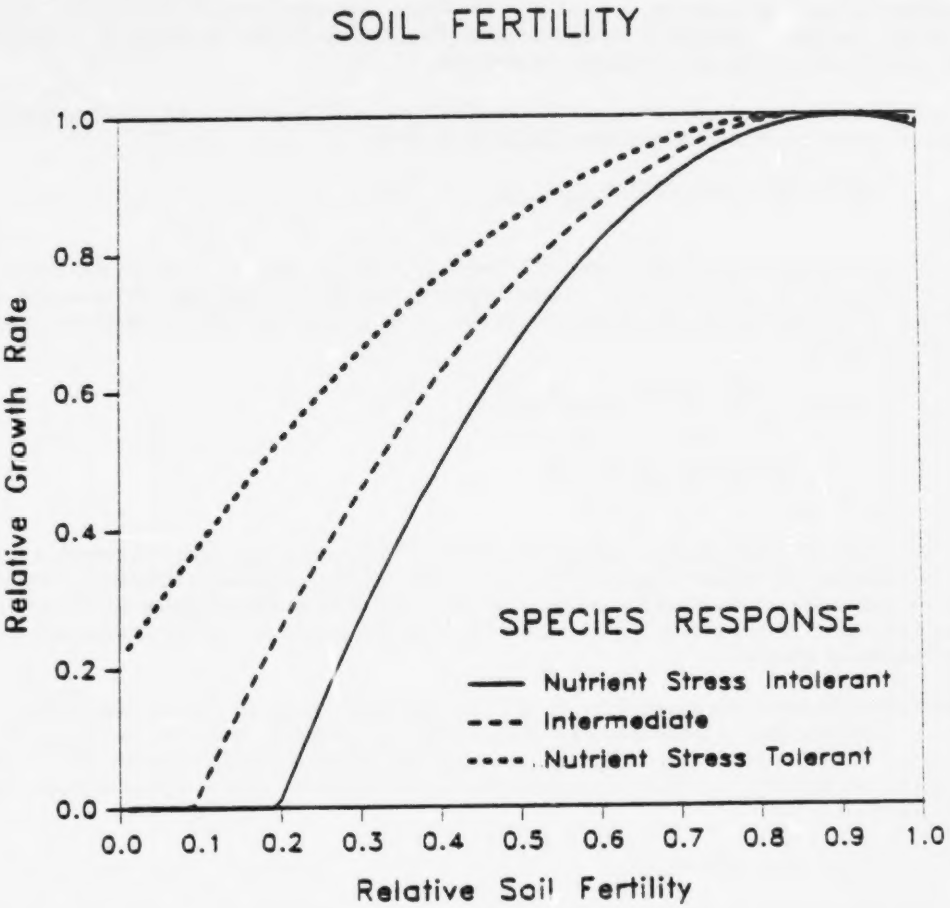

Figure A.4. Multiplier used to adjust tree growth rate in response to relative soil fertility.

Demographics

Regeneration is stochastic, and incorporates stump sprouting as well as seedling establishment. Sprouting depends on the number and sizes of newly dead trees on a plot, and on the tendency of a species to sprout. Seedling establishment is based on maximum potential inseeding rates for each species as constrained by ground-level shading, soil moisture, and soil fertility. Seedlings are filtered (sensu Harper 1977) through three years of environmental constraints before they are established as saplings. In ZELIG, the number of sprouts and the constrained inseeding rates are used to define a probability of establishment for each species, and new trees are established stochastically according to these probabilities. This algorithm, while simplistic, biases regeneration to reflect the prevalence of stump-sprouting in eastern forests, and adjusts the number and species composition of seedlings according to local site conditions. As with other FORET-class models, ZELIG assumes that any species included in the simulation may be established if site conditions are appropriate; there are no constraints to reflect seed availability or dispersal.

Annual diameter growth is based on species-specific functions relating volumetric growth to the current size (height and diameter) of an individual tree (Botkin et al. 1972):

$$d[D^2H]/dt = rL(1.0-DH/D_{max}H_{max}), \qquad (6)$$

where D is diameter at breast height (cm), H is height (cm), D_{max} and H_{max} are the maximum attainable diameter and height for a given species, r is relative growth rate, and L is leaf area. By making a number of simplifying assumptions about tree allometries, Botkin et al. (1972) were able to specify an equation for diameter increment:

$$dD/dt = \frac{GD(1.0-DH/D_{max}H_{max})}{(274.0+3.0b_2D-4.0b_3D^2)} \qquad (7)$$

where the b's are allometric constants and G is a growth rate parameter that can be expressed in terms of the other variables (but see section on parameterization). This equation is admittedly simplistic in that it does not attend the complexities of photosynthate allocation within a tree. It offers the advantage that it seems to capture the essential pattern of tree growth (Figure 5), and can be readily parameterized with comparable accuracy for a large number of species.

Mortality is modeled as a stochastic event, and may arise from 2 sources: natural (age-related) mortality, and stress or suppression. Natural mortality related to aging is stochastic, based on the assumption that 1% of individuals survive to reach a species-specific maximum age (Botkin et al. 1972, Shugart 1984). The further assumption that mortality is constant dictates, for suitably long lifespans, that the annual mortality rate can be approximated as:

$$m = 4.605/A_{max}, \qquad (8)$$

where 4.605 derives from the natural log of 0.01 (1%) and A_{max} is maximum age in years. Stressed individuals (those failing to achieve 10% of their potential growth increment, or achieving an absolute increment of less than 0.1 cm, for more than 2 consecutive years) are subjected to a mortality rate that assumes that only 1% of stressed trees will survive 10 years; this yields a mortality rate for stressed trees of 0.369. The criterion that a tree must grow at least 0.1 cm in diameter to escape stress mortality injects an element of age-dependence into mortality: as a tree approaches its maximum diameter (in old age), its maximum possible increment approaches 0.0 and it enters the domain of stress mortality. While this approach is motivated largely by computational convenience (the model need not account tree age), the resultant mortality patterns are largely consistent with data from tree life tables (Harcombe 1987).

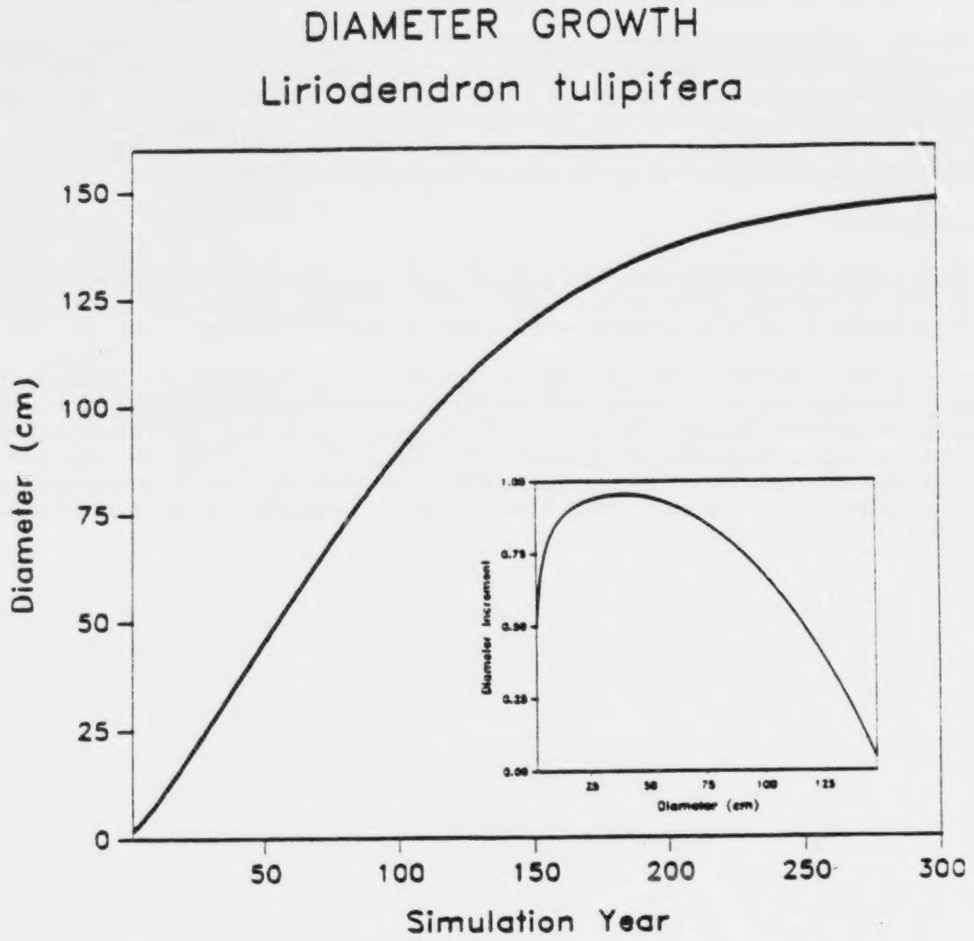

Figure A.5. Diameter growth as simulated by the forest model. Inset: relation of diameter increment to current diameter.

Simulations

In gap models, a model plot is typically large enough to contain the influence of a large tree's dominance and death, without overly diluting this influence (Shugart and West 1979). ZELIG is implemented as an array of 0.04-ha cells. The array is underlain by a soils map (representing a topographic gradient), providing for variation in soil moisture and site productivity. The array of plots is simulated simultaneously, so that each plot experiences the same temperature and precipitation regime. Thus, temporal variation in weather constraints as well as spatial variation in edaphic constraints are incorporated into the simulation.

Because the simulator is stochastic, a single plot depicts a possible trajectory of forest dynamics, but not necessarily the mean or expected trajectory. Thus, the model typically is run for a large number of replicate plots, and these are aggregated to describe the average trajectory of forest dynamics over time. Shugart (1984) and Smith and Urban (in press) have used gap models to illustrate the relationship between gap-scale dynamics and larger-scale forest dynamics. Preliminary simulations with the ZELIG model suggest that at least 30 replicate plots are necessary to stabilize the variance in basal area or biomass.

Parameterization

Implementing the ZELIG program for a particular study site requires parameter estimates for tree species silvics, soil characteristics, and a weather regime. These parameters are generally readily available from published sources, or are easily estimated without additional on-site field studies.

Tree species parameters used in this study are annotated in Appendix Table A.1. These parameters are based on silvicultural records in Fowells (1965) and Harlow and Harrar (1969), and preliminary estimates were computed as described elsewhere (Botkin et al. 1972, Shugart 1984, Solomon 1984, Pastor and Post 1985). Because of the lack of site-specific data of sufficient scope and resolution to calibrate the model over the broad spectrum of forests considered in this study, these parameter estimates have not been adjusted to reproduce any particular target forest. Therefore, model results should be interpreted cautiously, at a coarse level of resolution.

Table A.1. Parameter[1] Estimates for 45 Tree Species Used in Simulations of Southeastern Forests

	A, D, H_{max}	G	L D N F	Sprouts, Seeds	$GDD_{min, max}$
ACNE	Acer negundo Boxelder				
	75 100 2500	215	2 2 3 3	1 2.5 100.0 40	900 5200
ACRU	Acer rubrum Red maple				
	150 125 3500	175	2 2 3 3	1 2.5 100.0 40	1250 6600
ACSI	Acer saccharinum Silver maple				
	125 150 3500	230	2 2 2 3	1 2.5 100.0 40	1300 4700
CACO	Carya cordiformis Yellowbud hickory				
	250 125 5000	165	3 3 2 1	1 2.5 100.0 20	1900 5000
CAGL	Carya glabra Pignut hickory				
	300 100 4000	115	3 3 2 1	1 2.5 100.0 20	1900 4500
CAOL	Carya ovalis Red hickory				
	300 125 4500	125	3 4 2 1	1 2.5 100.0 20	1900 5500
CAOT	Carya ovata Shagbark hickory				
	250 125 4000	135	3 4 2 1	1 2.5 100.0 20	1650 5000
CATO	Carya tomentosa Mockernut hickory				
	300 100 3500	100	3 4 2 1	1 2.5 100.0 20	1900 6000
CELA	Celtis laevigata Sugarberry				
	200 75 3000	125	2 3 1 2	1 2.5 100.0 30	2650 7000
COFL	Cornus florida Dogwood				
	100 35 1250	105	1 4 1 1	1 2.5 35.0 30	1900 6000
DIVI	Diospyros virginiana Persimmon				
	150 50 2000	115	4 3 2 3	1 2.5 50.0 30	2650 6900
FAGR	Fagus grandifolia Beech				
	350 150 3700	90	1 2 2 1	1 2.5 30.0 20	1300 5500
FRAM	Fraxinus americana White ash				
	250 150 3500	100	3 4 1 2	1 2.5 20.0 30	1400 6000
FRPE	Fraxinus pensylvanica Green ash				
	150 125 3250	140	3 1 1 3	1 2.5 20.0 30	1050 5500
LIST	Liquidambar styraciflua Sweetgum				
	250 125 3500	120	4 4 2 3	1 2.5 100.0 30	2650 6000
LITU	Liriodendron tulipifera Tuliptree				
	300 300 6000	170	4 3 1 1	1 2.5 100.0 40	1900 6000

Table A.1. continued

			A, D, H_{max}		G	L D N F				Sprouts, Seeds				$GDD_{min, max}$	
MAGR	Magnolia grandiflora Southern magnolia	300	200	4000	115	3	2	1	2	1	2.5	100.0	20	3500	6000
NYAQ	Nyssa aquatica Swamp tupelo	300	150	3500	100	4	1	2	5	1	2.5	100.0	20	3000	6000
NYSY	Nyssa sylvatica Black gum	300	150	4000	115	3	4	1	3	1	2.5	100.0	30	1900	7000
PECH	Pinus echinata Shortleaf pine	200	125	4000	170	5	5	3	1	1	2.5	15.0	40	2650	5100
PELL	Pinus elliotti Slash pine	200	100	3500	150	4	3	3	2	0	0.0	0.0	40	4000	6000
PPAL	Pinus palustris Longleaf pine	250	125	4500	150	5	3	3	2	0	0.0	0.0	40	4000	6500
PSER	Pinus serotina Pond pine	200	100	3500	150	5	2	2	3	0	0.0	0.0	40	3500	6000
PTAE	Pinus taeda Loblolly pine	250	150	5500	185	4	4	3	2	0	0.0	0.0	40	3150	6000
PLOC	Platanus occidentalis Sycamore	400	300	5200	110	4	1	1	3	1	2.5	50.0	30	1900	5500
PODE	Populus deltoides Cottonwood	200	200	5300	205	5	1	2	4	1	2.5	50.0	40	1700	5300
PRSE	Prunus serotina Black cherry	200	125	4000	170	4	3	1	1	1	2.5	100.0	30	2100	6000
QALB	Quercus alba White oak	400	200	4500	95	3	4	2	1	1	2.5	100.0	20	1700	5500
QCOC	Quercus coccinea Scarlet oak	300	150	3100	90	4	5	3	1	1	2.5	100.0	20	2000	4500
QFAL	Quercus falcata Southern red oak	300	200	3750	110	3	4	2	2	1	2.5	100.0	20	2650	6000
QLAU	Quercus laurifolia Laurel oak	300	200	3000	90	3	2	2	2	1	2.5	100.0	20	4000	6500
QLYR	Quercus lyrata Overcup oak	300	150	3500	100	3	1	2	3	1	2.5	100.0	20	2900	5300

Table A.1. continued

		A, D, H_{max}			G	L D N F				Sprouts, Seeds				$GDD_{min, max}$	
QMAR	Quercus marilandica Blackjack oak	300	50	1500	45	3	6	3	1	1	2.5	50.0	20	2500	6000
QMIC	Quercus michauxii Swamp chestnut oak	300	200	4000	115	3	2	2	1	1	2.5	100.0	20	3000	5500
QNIG	Quercus nigra Water oak	300	100	4000	110	3	2	2	3	1	2.5	100.0	20	3000	6000
QPHE	Quercus phellos Willow oak	300	150	4000	115	3	3	2	3	1	2.5	100.0	20	3500	5500
QPRI	Quercus prinus Chestnut oak	300	125	4500	125	3	5	3	1	1	2.5	100.0	20	1900	4100
QRUB	Quercus rubra Northern red oak	300	200	5000	130	3	4	2	1	1	2.5	100.0	20	2000	4600
QSHU	Quercus shumardii Shumard oak	300	200	5500	140	3	4	2	2	1	2.5	100.0	20	2400	6000
QSTE	Quercus stellata Post oak	400	125	3000	65	3	5	3	1	1	2.5	100.0	20	2650	6000
QVEL	Quercus velutina Black oak	300	125	4500	125	3	5	3	1	1	2.5	100.0	20	1800	5100
SANI	Salix nigra Black willow	200	250	4300	185	5	1	2	4	1	2.5	20.0	40	1700	5500
TADI	Taxodium distichum Baldcypress	500	300	4500	80	3	2	2	5	0	0.0	0.0	20	3000	7000
TIHE	Tilia heterophylla White basswood	150	125	4300	245	2	2	1	2	1	2.5	100.0	30	2650	4600
ULAM	Ulmus americana American elm	300	200	4500	115	3	4	2	3	1	2.5	30.0	30	1200	7000

---

[1] A, D, and H_{max} are maximum age (yrs), diameter (cm), and height (cm) per species; G is growth rate constant; L, D, N, F are light (1=shade-tolerant), drought (/10=maximum tolerable drought- days), nutrient (1=stress intolerant), and flood tolerance (1=flood intolerant) classes, respectively; sprouting parameters are number, and minimum and maximum sproutable stump sizes (cm), Seeds is relative inseeding rate (stems/plot); $GDD_{min, max}$ are minimum and maximum growing degree-days.

ANCIENT ANALOGS FOR GREENHOUSE WARMING OF CENTRAL CALIFORNIA

by

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FINDINGS[1]

Using vegetation records from five sites in the Sierra Nevada, two periods are evaluated as historic analogs for greenhouse warming. During the early-Holocene, 9000 years ago, the vegetation of the western Sierra Nevada resembled that currently found east of the crest. Xeric pine forest occupied areas now covered by Sierra montane forest, precipitation was less and temperatures may have been cooler. Concurrently, precipitation east of the Sierra crest may have been higher than today. By 6000 years ago, the modern vegetation zones had become established on both sides of the Sierra Nevada. Some sites indicate precipitation greater than today, whereas others indicate less. Temperatures were lower at most sites.

These results are based on two numerical techniques, dissimilarity analysis and detrended correspondence analysis, that indicate modern analogs for fossil samples. The best modern analogs for each sample are converted into precipitation and temperature estimates using modern lapse rates for the area.

Tourism, water supply, and the logging industry will be negatively affected if precipitation changes during the next century are in the direction and magnitude of those of the 9000-yr B.P. analog. Increased precipitation in the eastern Sierra could offset some of the effects.

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CHAPTER I

INTRODUCTION

PAST WARM PERIODS AS ANALOGS FOR GREENHOUSE WARMING

There are two alternatives for evaluating the potential effects of greenhouse warming on our ecosystems. The first is to use computer models that translate estimates of precipitation, temperature, and other factors into diversity, biomass, runoff, or other ecosystem parameters. The second alternative, the one used in this investigation, is to study the responses of ecosystems during times in the past when the climate was substantially warmer than at present.

The success of the analog approach depends in part on how closely past environments duplicate those of interest. A historical analog for greenhouse warming should match the atmospheric, geographic, and climatic factors predicted for the next century. Possible analogs for warmer climate include the 1930's, the medieval warm period of A.D. 1100 to 1250, the postglacial warmth maximum, or the Cretaceous period. However, the atmospheric concentration of CO_2 was probably lower than today during the first two periods; and although CO_2 concentrations may have been higher than at present during the Cretaceous, geographic and other environmental conditions were vastly different.

During the maximum of post-glacial warmth, summer temperatures were 2-3°C warmer than today, and CO_2 concentrations may have been 30 ppm greater than the pre-industrial average (Neftel et al., 1982). Although traditional scenarios have postulated a thermal maximum about 6000 years ago (Deevey and Flint, 1957), more recent investigations in western North America indicate maximum summer temperatures 10,000 - 8000 ya, coincident with maximum insolation (Davis et al., 1985; Davis et al., 1986; Davis and Moratto, 1988; Elias, 1985; Hebda and Mathewes, 1984; Kearney and Luckman, 1983; Ritchie et al., 1983; Vance, 1985) .

Climate models such as NCAR's CCM (Kutzbach and Guetter, 1986; Kutzbach, 1987) indicate July temperatures 9000-yr B.P. in California ca. 2.5°C greater and no change in precipitation relative to today, compared with increases of 4.8°C (GISS) and 2.4°C (OSU model) and precipitation decreases of 0.09 and 0.32 mm day^{-1} predicted for $2xCO_2$ increases (prepared for this study). Six thousand years ago, the CCM indicates temperature ca. 1°C higher and precipitation much higher for a combined region of California and the American Southwest (Kutzbach, 1987). Precipitation and temperature reconstructions for California alone have not been published.

The primary cause of increased summer temperature in the early and mid-Holocene was greater solar radiation in the northern hemisphere, which was matched by decreased insolation in winter (Davis et al., 1986). January $2xCO_2$ model results for California are +4.8°C (GISS) and +2.7°C (OSU), whereas January temperature 9000-yr B.P. in California was the same as today according to the CCM (Kutzbach and Guetter, 1986). CCM reconstructions of January temperature 6000-yr B.P. are near modern values for most of North America (Webb et al., 1987). Because most the native plants in the Sierra Nevada are dormant during winter, the importance of the difference between the 9000 yr B.P. analog and $2xCO_2$ conditions is lessened, but it is an important consideration for other topics such as citrus production and winter crops.

THE HOLOCENE CLIMATIC HISTORY OF CALIFORNIA

California is presently a land of climatic contrasts, and its regions have had contrasting climatic histories. Coastal California was wet and cold during the last glaciation, whereas the western Sierra Nevada was dry (Davis et al., 1985). During the early Holocene, the western Sierra Nevada was drier than today, but the desert east of the Sierra Nevada was wetter (Spaulding and Graumlich, 1986; Davis and Moratto, 1988). Thus, the 9000-yr B.P. analog is different for each area. By 6000 years ago, the modern vegetation had become established at most sites in California. Both 6000 and 9000 yr B.P. may be considered analogs for greenhouse warming because the first period has traditionally been considered the time of maximum global warmth, and because the 9000-yr B.P. period has been shown to be warmer than today in western North America. Because the vegetation of the Sierra Nevada was different during these two periods, they provide a two alternative analogs for greenhouse warming.

In the rest of this report, I will describe the numerical techniques used to reconstruct the vegetation of the Sierra Nevada 9000 ya. The techniques of Dissimilarity Analysis and Detrended Correspondence Analysis both indicate the character of past vegetation by indicating the most similar modern vegetation sample via pollen analysis. Both techniques provide a measure of uncertainty by indicating numerically the degree of similarity. The reconstructions are further evaluated by comparing the climatic implications of the vegetation reconstructions with the outputs of the GISS and OSU climate models. Finally, I will address environmental and socioeconomic implications of the results and recommend policy changes.

CHAPTER 2

METHODOLOGY

THE DATA

The vegetation of the central Sierra Nevada is reconstructed using modern and fossil pollen samples collected by R. S. Anderson (1987) and Owen K. Davis (Davis et al., 1985; Davis and Moratto, 1988). Forty-four modern samples were collected from moss polsters in a west-east transect beginning in grassland at 400 m east of Fresno, California, reaching 3445 m above Granite Lakes north of Tioga Pass, and ending at 1280 m elevation at Fish Slough near Bishop, California (Anderson and Davis, 1988). The transect passes through all the major vegetation zones of the Sierra Nevada, but more samples were taken in forested vegetation where the fossil sites are located. The samples were taken in three sections (Fig. 1) rather than in one straight line, but this presents no problems to interpretation since no major north-south vegetation differences exist between the sampling localities, and the results are fully analogous to the two transects studied by Adam (1967).

The fossil samples come from five meadow and lake sites in the central Sierra Nevada (Anderson, 1987; Davis et al., 1985; Davis and Moratto, 1988). Balsam Meadow (2005 m), Exchequer Meadow (2219 m), and Starkweather (2438 m) are in Sierra montane forest, Tioga Pass Pond (3018 m) is in subalpine forest and Barrett Lake (2816 m) western subalpine forest (Figure 1). The age of the samples is established by 23 radiocarbon dates (Table 1).

Prior to the analysis of Balsam and Exchequer Meadows (Davis et al., 1985; Davis and Moratto, 1987), it was thought that the Sierran meadows came into existence in the late Holocene (Wood, 1975). The radiocarbon dates for Balsam and Exchequer Meadow (Table 1) document continuous and relatively uniform deposition of sediment since the late Pleistocene. The persistence of seeds and pollen of sedges and other wet-ground plants throughout the records indicate that these Sierran meadows have existed since the late Pleistocene.

Although pollen concentration and influx (accumulation rate) have been calculated for the sites (Davis, 1984, 1987; Anderson, 1987), pollen percentages have been used in the numerical analyses of the fossil data for two reasons. First, the surface sample data cannot be easily converted to concentrations or accumulation rates, and even if they are, the differences among samples could reflect site-specific processes rather than vegetation differences. Second, the pollen concentrations vary greatly among adjacent samples for the meadow sites, probably reflecting variable depositional processes rather than changes in plant abundances.

DISSIMILARITY COEFFICIENTS

Measures of dissimilarity permit the multivariate comparison of modern analogs with fossil samples. Low dissimilarity values among modern and fossil pollen samples indicate they originate in the same type of vegetation. Overpeck et al. (1985) tested eight dissimilarity indices by comparing 1618 different modern spectra from eastern North America with fossil samples from three sites. They found that squared chord distance often showed differences that the other coefficients could not.

In this study, calculations of squared chord distance are based on 15 pollen types that Anderson (1987) found to vary with elevation in the Sierra Nevada. The statistic is calculated as:

$$d_{ij} = \Sigma_k (p_{ik}^{1/2} - p_{jk}^{1/2})^2$$

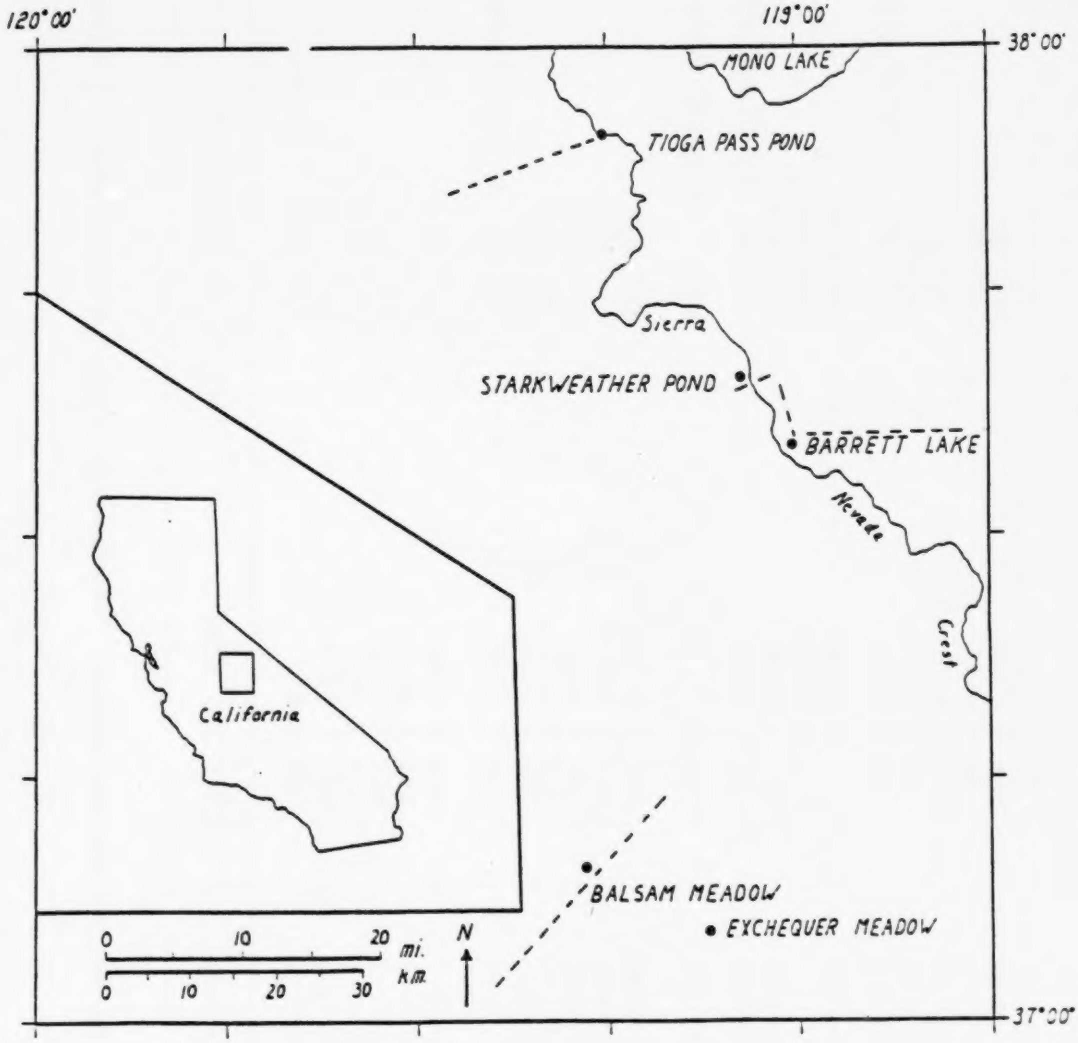
120°00'
119°00'
38°00'
37°00'
MONO LAKE
TIOGA PASS POND
Sierra
STARKWEATHER POND
BARRETT LAKE
Nevada
Crest
California
BALSAM MEADOW
EXCHEQUER MEADOW
0
10
20
mi.
0
10
20
30
km.
N

Figure 1. Map of the central Sierra Nevada, showing the location of sites studied in this report.

Table 1. Radiocarbon Dates for Central Sierra Nevada Pollen Sites

Site	Sediment Depth (cm)	Age (yr B.P.)	Laboratory No.
Balsam Meadow (2005 m)	(34-44)	470 ± 90	A-3688
	(54-64)	2350 ± 120	A-3689
	(81-91)	3160 ± 140	A-3690
	115-125	2920 ± 120	A-3691
	140-150	6160 ± 140	A-3692
	213-238	9420 ± 200	A-3693
Exchequer Meadow (2219 m)	55-65	1870 ± 60	Beta-16111
	90-200	2980 ± 80	Beta-17183
	172-180	4540 ± 90	Beta-17184
	205-230	7070 ± 70	Beta-16112
	284-291	11490 ± 270	Beta-17185
	326-351	10330 ± 380	Beta-16113
Starkweather Pond (2438 m)	213	10879 ± 150	AA-1133
Tioga Pass Pond (3018 m)	48-58	1910 ± 80	A-4448
	149-157	4060 ± 160	A-4449
	234-243	6100 ± 140	
	291-305	8760 ± 240	AA-4450
Barrett Lake (2816 m)	25-30	695 ± 85	SI-6676
	44-49	1110 ± 90	SI-6677
	74-80	470 ± 120	SI-6678
	85-90	3930 ± 90	SI-6679
	126-134	8020 ± 190	A-4455
	179-197	11730 ± 430	A-4456

Where d_{ij} is the dissimilarity between samples i and j, and p_{ik} is the proportion of pollen type k in sample i. The results are displayed graphically by representing each value as a shaded square from light (low dissimilarity) to dark (high dissimilarity) on a matrix with the data sets on the horizontal and vertical axes. This technique was proposed by L. J. Maher (1987). The utility of this approach is demonstrated by comparing the 44 modern samples with the averages for each of the seven major vegetation zones of the transect.

The sample with lowest dissimilarity is noted with an asterisk (*) if the value is less than 0.1. This "critical value" was chosen empirically. Lower values produce too many "misclassifications," i.e., too many samples are similar to averages of other vegetation zones. Higher critical values produce too few matches. Critical values of 0.15 and 0.12 are proposed for the squared chord distance by Overpeck et al. (1985), using data from eastern North America.

DETRENDED CORRESPONDENCE ANALYSIS

A second technique for finding analogs is to arrange samples along axes of variation of multivariate data, a technique known as ordination. Similar samples group together when plotted on these axes. Detrended correspondence analysis was performed with the DECORANA program (Hill, 1979) using the same 15 pollen types used in dissimilarity analyses. Both modern and fossil samples were included in the calculations to reduce the probability that fossil samples might spuriously plot close to some modern sample (Jacobsen and Grimm, 1986). For the same reason, each fossil site was analyzed separately; that is, analyzing several sites together could result in patterns reflecting differences among the fossil sites, rather than differences between the fossil and modern samples. Modern samples are plotted as symbols by vegetation type. Fossil samples are plotted as thousand-year averages connected by a solid line. Only the first two DCA axes are shown. The technique is illustrated by comparing the modern data set with Adam's (1967) 21 samples. For example, the first value (1) is the average of all values from 0 to 1000 yr B.P., the second number (2) ranges from >1000 to 2000 yr B.P., and so on.

CHAPTER 3

RESULTS

THE POLLEN DATA

The Surface Samples

A major feature of the modern sample transect (Figure 2) is the positive correlation between elevation and Pinus pollen, which exceeds 60% of the pollen sum in samples from forest vegetation, and is less than 35% in grassland samples west of the Sierra Nevada, and less than 40-50% in the Great Basin samples east of the Sierra crest. Distinctive pollen assemblages occur for each of the seven major vegetation zones. These vegetation types are used informally to facilitate discussion of the modern vegetation and the comparison with vegetation descriptions for the Sierra Nevada (see Anderson and Davis, 1988, for a more complete discussion). The differences among vegetation and pollen samples within the zones, such as those demonstrated by the numerical analyses of this study, do not detract from the utility of the zone concept.

Relatively few samples were collected at low elevation, so the four lowest samples from the western Sierra, grassland, oak woodland, and chaparral, are lumped into a "oak grassland" (GR) zone dominated by the pollen of Quercus, Gramineae, and Other Compositae. Sierra montane (SM) samples are dominated by 10-30% Abies pollen, with Cupressaceae reaching 30% below 2000 m. Upper montane (UM) and eastern subalpine (ES) samples contain up to 30% Tsuga pollen. Subalpine (SA) samples are characterized by the dominance (>80%) of Pinus pollen derived from Pinus murrayana and P. flexilis, which form treeline in this part of the Sierra Nevada. Sample 29 (3445 m) was collected above treeline. It too has a high (87%) pine pollen percentage. Pine forest (PF) samples contain high Artemisia and moderate Abies percentages. Low elevation samples east of the crest contain up to 50% Artemisia pollen and 5-10% Sarcobatus pollen.

The Fossil Sites

The four sites west of the Sierra crest have similar stratigraphies. The upper portions of the diagrams are dominated by high (70-90%) Pinus percentages, whereas Gramineae, Other Compositae, and Artemisia percentages are high near the base. Abies percentages increase gradually from the base to the surface. The Balsam Meadow pollen diagram (Figure 3) shows this transition between 160 and 180 cm. At Exchequer Meadow (Figure 4) the transition takes place between 200 and 300 cm., and at Starkweather Pond (Figure 5), between 180 and 190 cm. At Tioga Pass Pond it takes place at the base of the diagram (Figure 6) below 300 cm.

The Barrett Lake diagram (Figure 7) is dominated by very high Pinus percentages. Above 100 cm, Abies and Tsuga percentages increase, and Artemisia percentages decrease.

DISSIMILARITY INDICES

Comparison of Modern Samples

The dissimilarity diagram (Figure 8) shows a general correspondence between individual samples and the vegetation zone averages. The oak grassland, upper montane, subalpine, eastern subalpine, and Great Basin zones are homogeneous, but the Sierra montane and pine forest groups are not. Within the oak grassland (GR) zone, sample 3 has a minimum dissimilarity greater than 0.1. Half of the Sierra montane (SM) samples are dissimilar (>0.1 dissimilarity) to the zone averages, with two samples (16 & 17) more similar (<0.1 dissimilarity) to the subalpine zone averages than to SM values. Four of the five upper montane (UM) samples have dissimilarity values less than 0.1. Both the subalpine (SA) and eastern subalpine (ES) samples are internally consistent, being most similar to their respective zone averages at less than 0.1 dissimilarity. None of the six pine

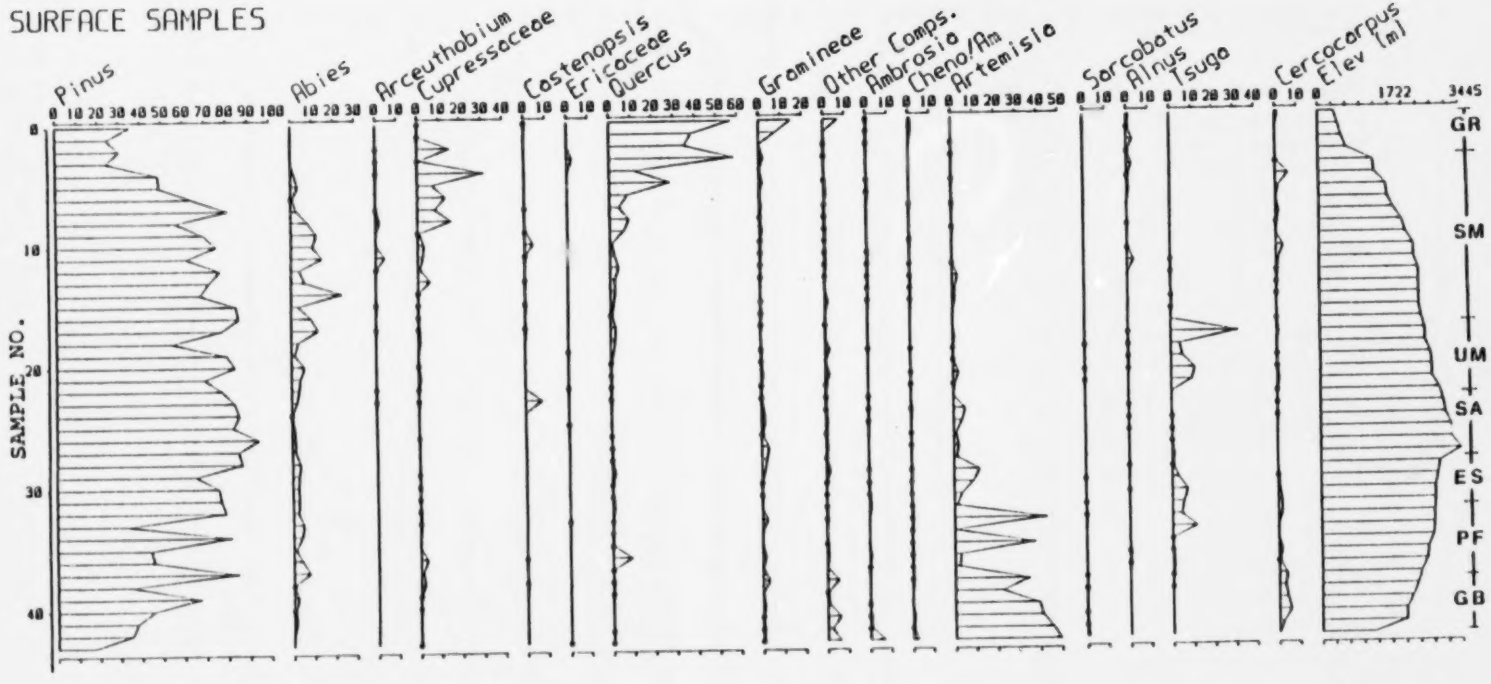

Figure 2. Percentage pollen diagram of 144 modern samples collected in a transect across the central Sierra Nevada. Abbreviations in right margin refer to different vegetation types. GR = oak grassland, SM = Sierra Montane, UM = Upper Montane, SA = Subalpine, ES = Eastern Subalpine, PF = Pine Forest, and GB = Great Basin.

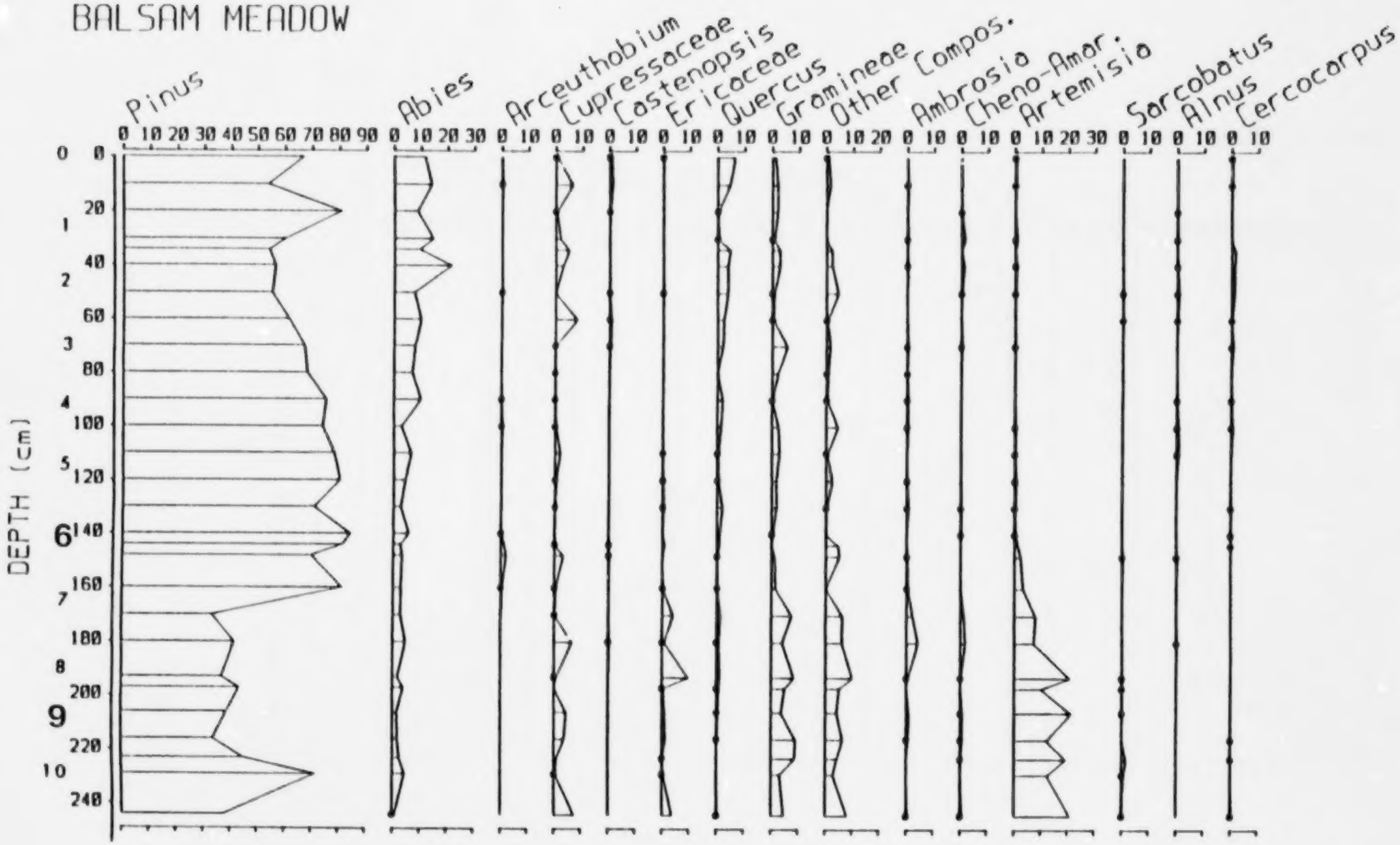

Figure 3. Percentage pollen diagram for Balsam Meadow, Fresno Co., California. Dots indicate less than 1%. Numbers next to depth column are ages in thousands of radiocarbon years.

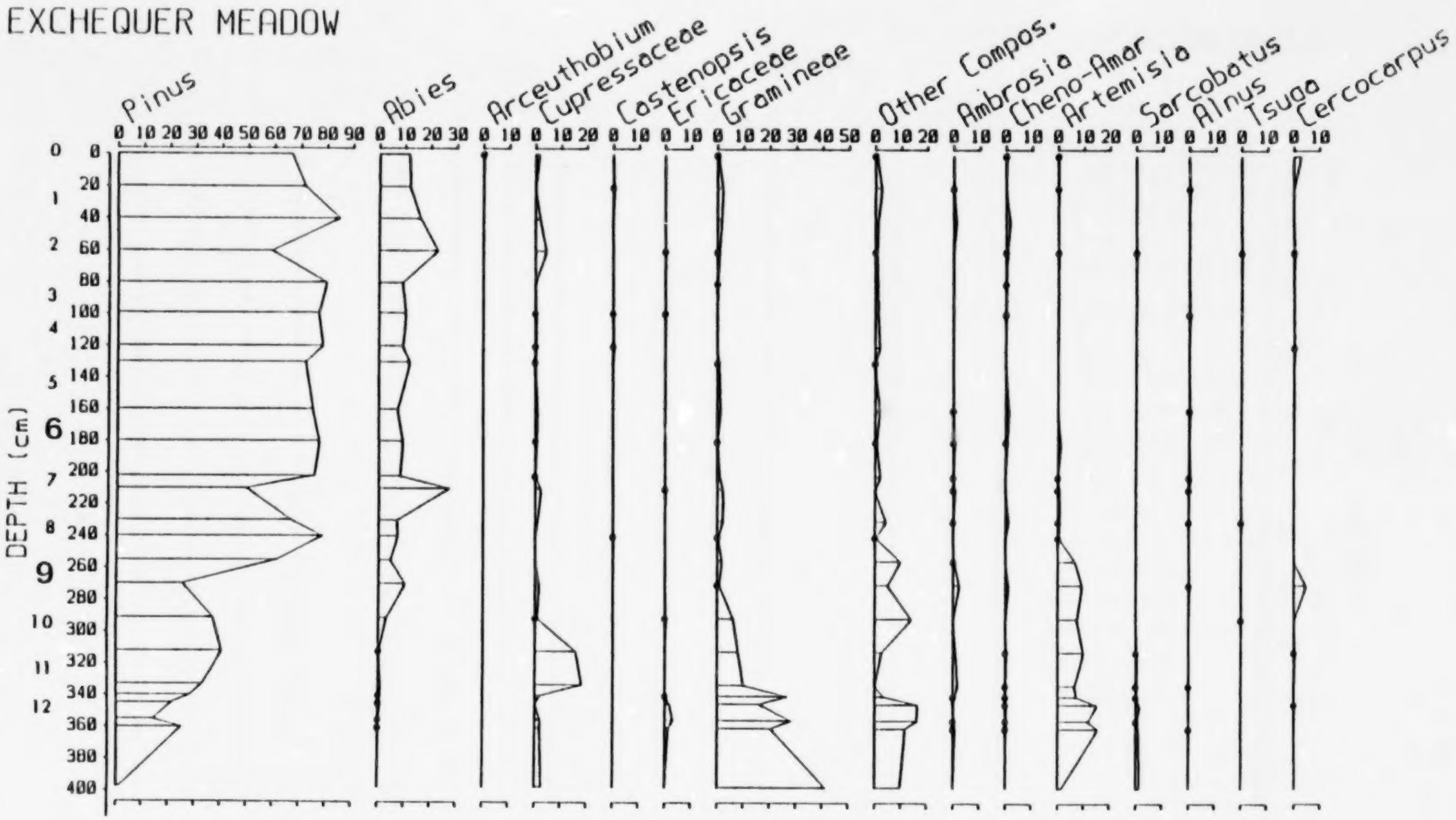

Figure 4. Percentage pollen diagram for Exchequer Meadow, Fresno Co., California. Dots indicate less than 1%. Numbers next to the depth column are ages in thousands of radiocarbon years.

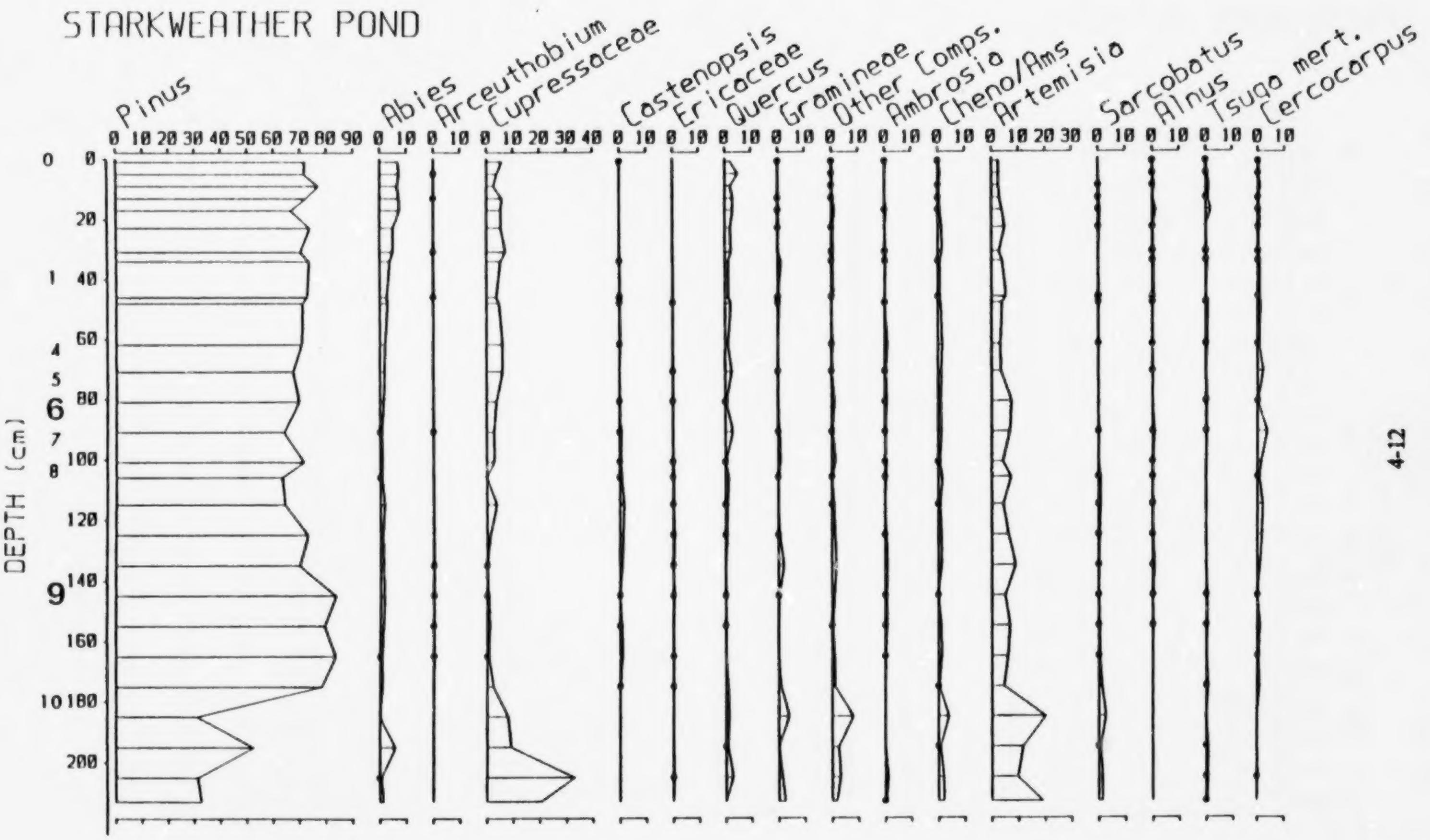

Figure 5. Percentage pollen diagram for Starkweather Pond, Madera Co., California. Dots indicate less than 1%. Numbers next to the depth column are ages in thousands of radiocarbon years.

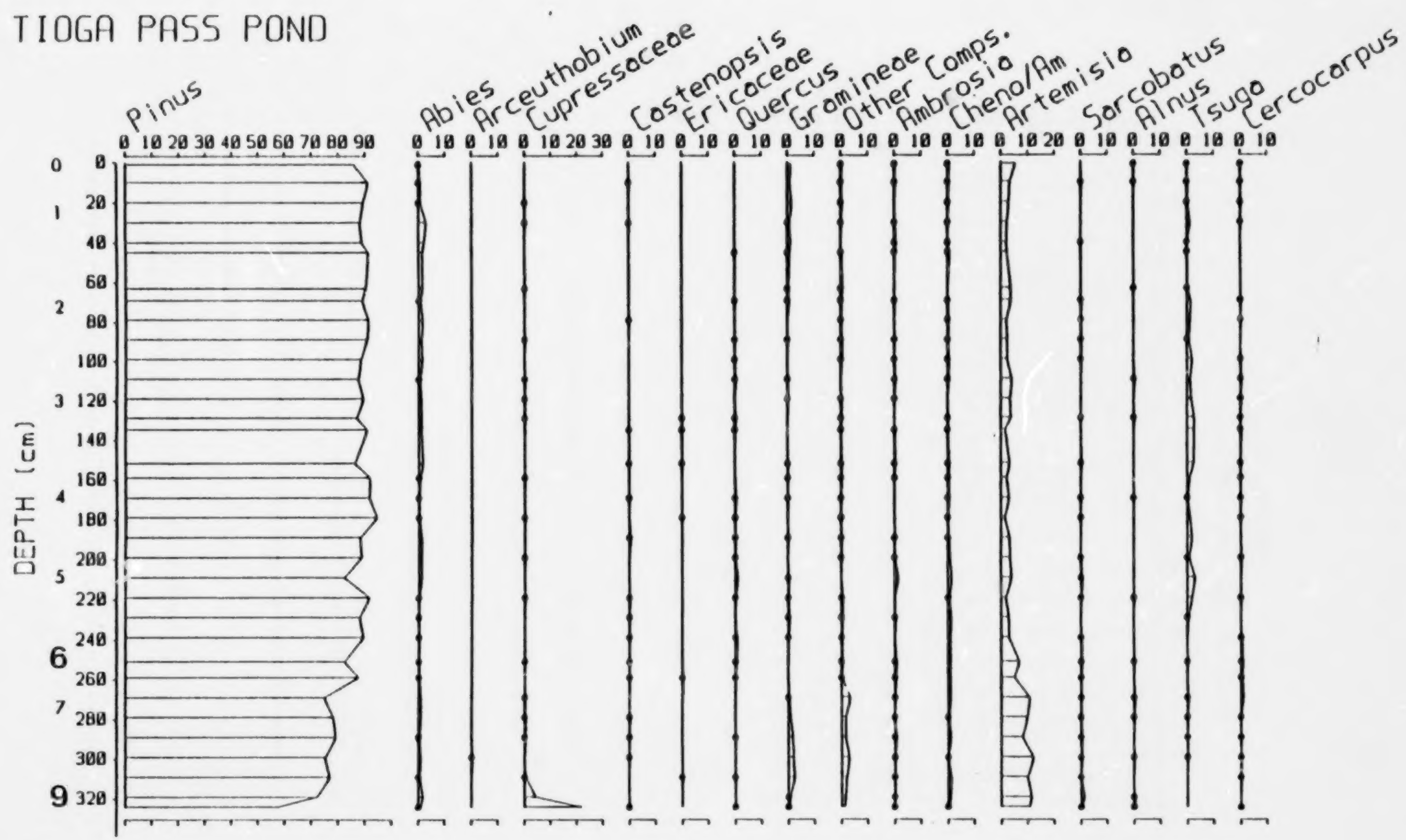

Figure 6. Percentage pollen diagram for Tioga Pass Pond, Mono County, California. Dots indicate less than 1%. Numbers next to depth column are ages in thousands of radiocarbon years.

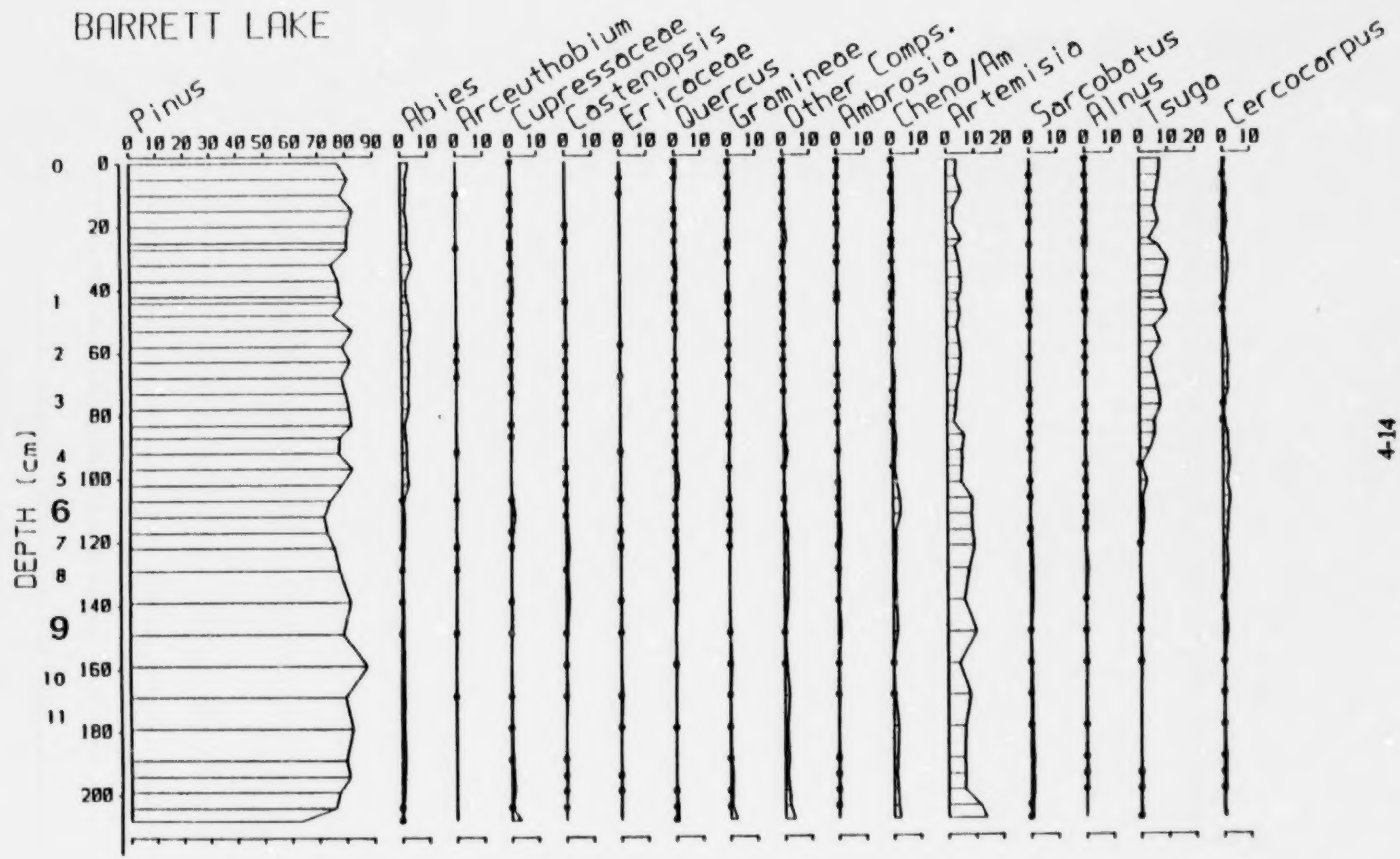

Figure 7. Percentage pollen diagram for Barrett Lake, Mono County, California. Dots indicate less than 1%. Numbers next to depth column are ages in thousands of radiocarbon years.

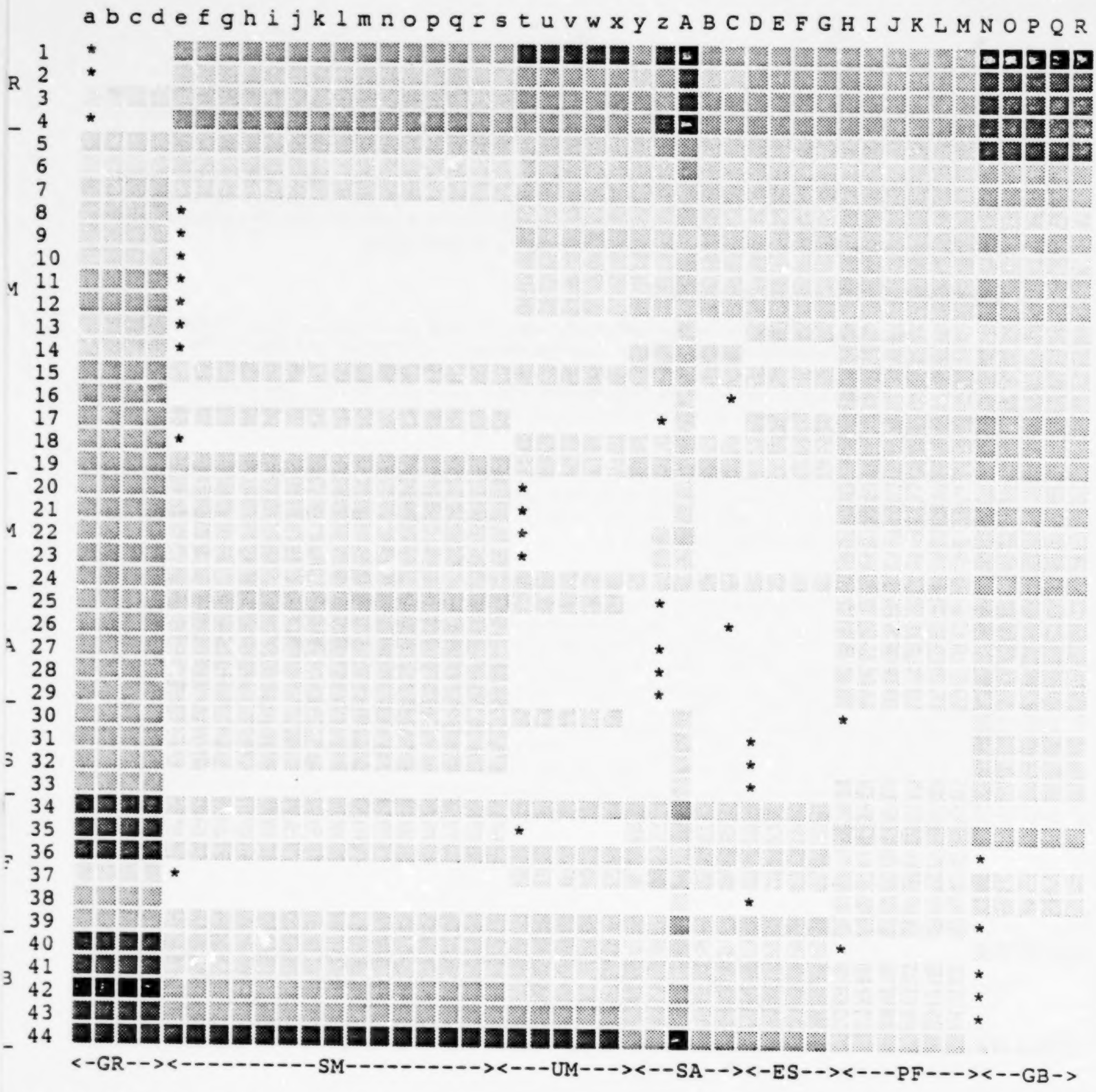

Figure 8. Dissimilarity diagram comparing 44 modern pollen samples with averages for each vegetation zone. GR = oak grassland, SM = Sierra Montane Forest, UM = Upper Montane Forest, SA = subalpine, ES = eastern subalpine, PF = pine forest, and GB = Great Basin Steppe.

Horizontal Axis = Modern Pollen Samples Sierra Nevada Zone Averages
Vertical Axis = Modern Pollen Samples Sierra Nevada

forest (PF) samples is similar to the zone averages. Five of the six are most similar (<0.1 dissimilarity) to the averages of various other zones. One of the five Great Basin samples is similar to the eastern subalpine averages, and one has high (>0.1) dissimilarity to the GB averages.

Dissimilarity analysis fails to match one-third of the samples to their zones. Nine (20%) of the samples do not match any zone average (>0.1 dissimilarity), and 8 (18%) of the 44 samples are similar to the wrong zone averages (<0.1 dissimilarity). The fossil dissimilarity diagrams must be interpreted with these errors in mind. General trends should be apparent, but occasional mismatches are anticipated.

Dissimilarity of Fossil and Modern Samples

The dissimilarity diagrams for the five fossil sites (Figures 9-13) form U-shaped patterns of low-dissimilarity (<0.1) samples surrounded by high-dissimilarity values on the sides and bottoms of the figures. The sides are dissimilar to fossil values because they are never similar to low-elevation vegetation, the bottoms are dissimilar because the early-Holocene vegetation was different from any of the modern analogs. The transition from the no-analog vegetation of the early Holocene occurs shortly after 9000 yr B.P. at Balsam, Exchequer, and Tioga, and is earlier at Starkweather.

The early-Holocene samples from Balsam, Exchequer, and Starkweather are similar (<0.1 dissimilarity) to samples east of the Sierra crest. At each of the three sites, the transition to similarity with western samples takes place ca. 9000 yr B.P. Tioga and Barrett also show this trans-Sierran similarity transition, but during a late Holocene (Tioga) and early Holocene (Barrett).

Prior to ca. 7000 yr B.P., the Balsam Meadow samples (Figure 9) are similar to modern analogs in the pine forest and eastern subalpine zones. From 7000 to ca. 3000 yr B.P., the fossil samples match the upper SM and UM zones. After 3000 yr B.P., the fossil samples are generally most similar to sample j, collected at the site. The Exchequer Meadow samples (Figure 10) are similar to western Sierra analogs prior to ca. 8200 yr B.P. Most of the Holocene samples are match samples from the upper Sierra montane forest. Although four of the samples (3, 13, 14, and 25) from Starkweather Pond (Figure 11) appear to be misclassified, the general pattern is similar to that for Balsam and Exchequer. The east-west similarity transition takes place ca. 9000 yr B.P., early Holocene samples are similar to upper montane and subalpine analogs, and little change is evident after ca. 6000 yr B.P. Most of the Tioga Pass Pond samples (Figure 12) are similar to subalpine samples from west of the crest, but samples 14-16 (ca. 3500 yr B.P.) match samples from east of the crest. The Barrett Lake samples (Figure 13) are primarily similar to samples from the eastern subalpine forest, but samples 28-35 (7900-12,100 yr B.P.) are similar to samples from west of the Sierra crest.

DETRENDED CORRESPONDENCE ANALYSIS

Comparison of Modern Samples

Figure 14 compares the 44 modern samples with a comparable set of samples collected in a west-to-east transect across Tioga Pass by David Adam (1967). A line is drawn around each cluster to facilitate discussion. Samples from the two low-elevation zones -- oak grassland and Great Basin steppe -- form distinct groups at the lower left and extreme right margins of the plots. The forested types form overlapping groups toward the top of the diagrams, with the Sierra montane and upper montane samples to the left, and the subalpine, eastern subalpine, and pine forest samples to the right.

This general pattern also appears in the fossil diagrams (Figures 15-19): the first axis provides a west-east ordination of the samples, the second axis is primarily an elevational ordination. Note that the polarity (left-right, up-down) of the axes shifts from figure to figure. For example, western Sierra samples plot to the left in Figures 14, 15, and 16, but to the right in Figures 17, 18, and 19. A possible climatic interpretation is that the

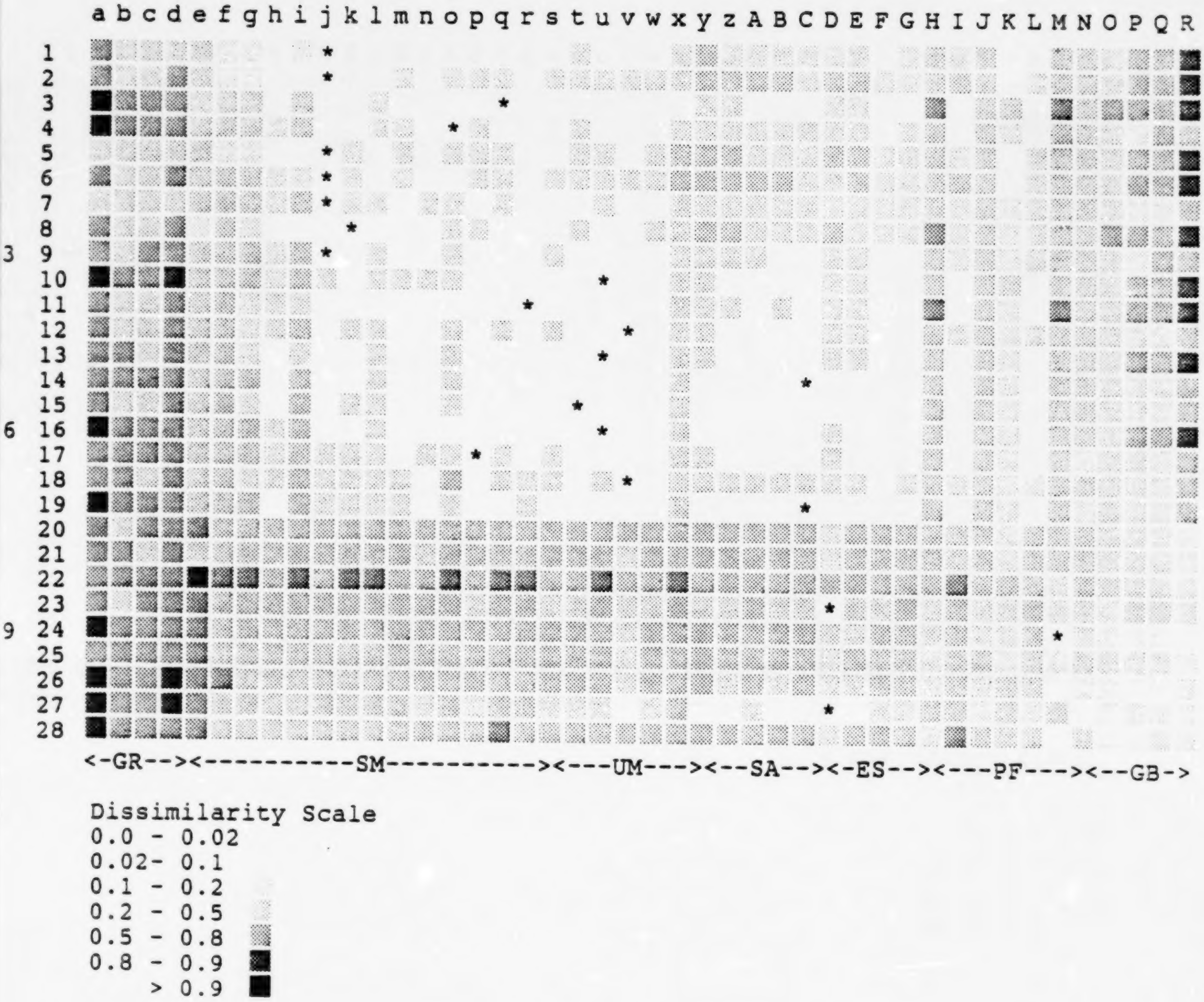

Figure 9. Dissimilarity diagram comparing Balsam Meadow pollen samples with 44 modern pollen samples. Asterisks mark the most-similar modern samples. Numbers on extreme left refer to ages of the samples (3, 6, and 9,000 yr B.P.). GR = oak grassland, SM = Sierra Montane Forest, UM = Upper Montane Forest, SA = subalpine, ES = eastern subalpine, PF = pine forest, and GB = Great Basin Steppe.

Horizontal Axis = Modern Pollen Samples Sierra Nevada
Vertical Axis = BALSAM MEADOW FRESNO CO. CA

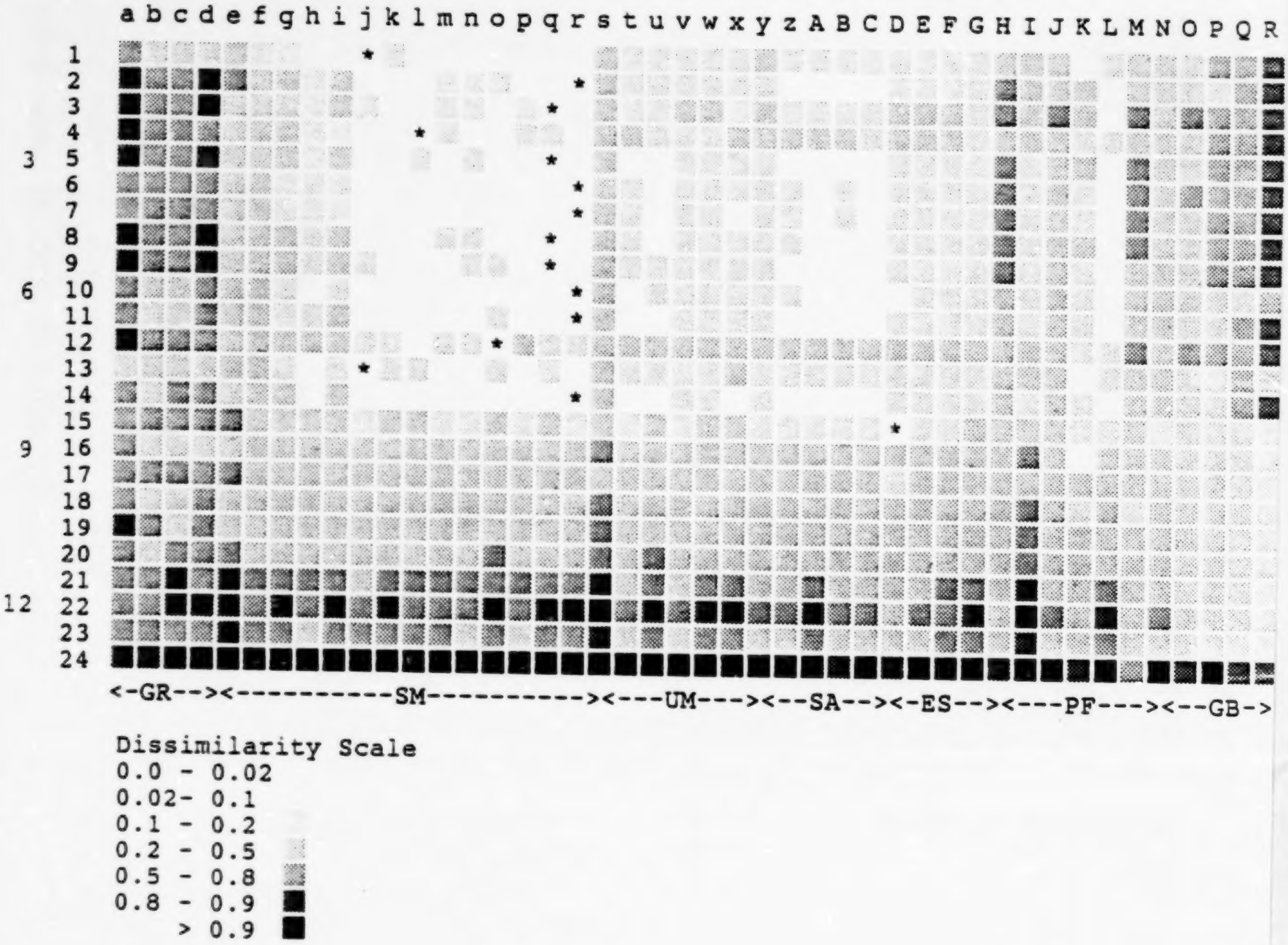

Figure 10. Dissimilarity diagram comparing Exchequer Meadow pollen samples with 44 modern pollen samples. Asterisks mark the most-similar modern samples. Numbers on extreme left refer to ages of the samples (3, 6, and 12,000 yr B.P.). GR = oak grassland, SM = Sierra Montane Forest, UM = Upper Montane Forest, SA = subalpine, ES = eastern subalpine, PF = pine forest, and GB = Great Basin Steppe.

Horizontal Axis = Modern Pollen Samples Sierra Nevada
Vertical Axis = Exchequer Meadow Fresno Co. CA

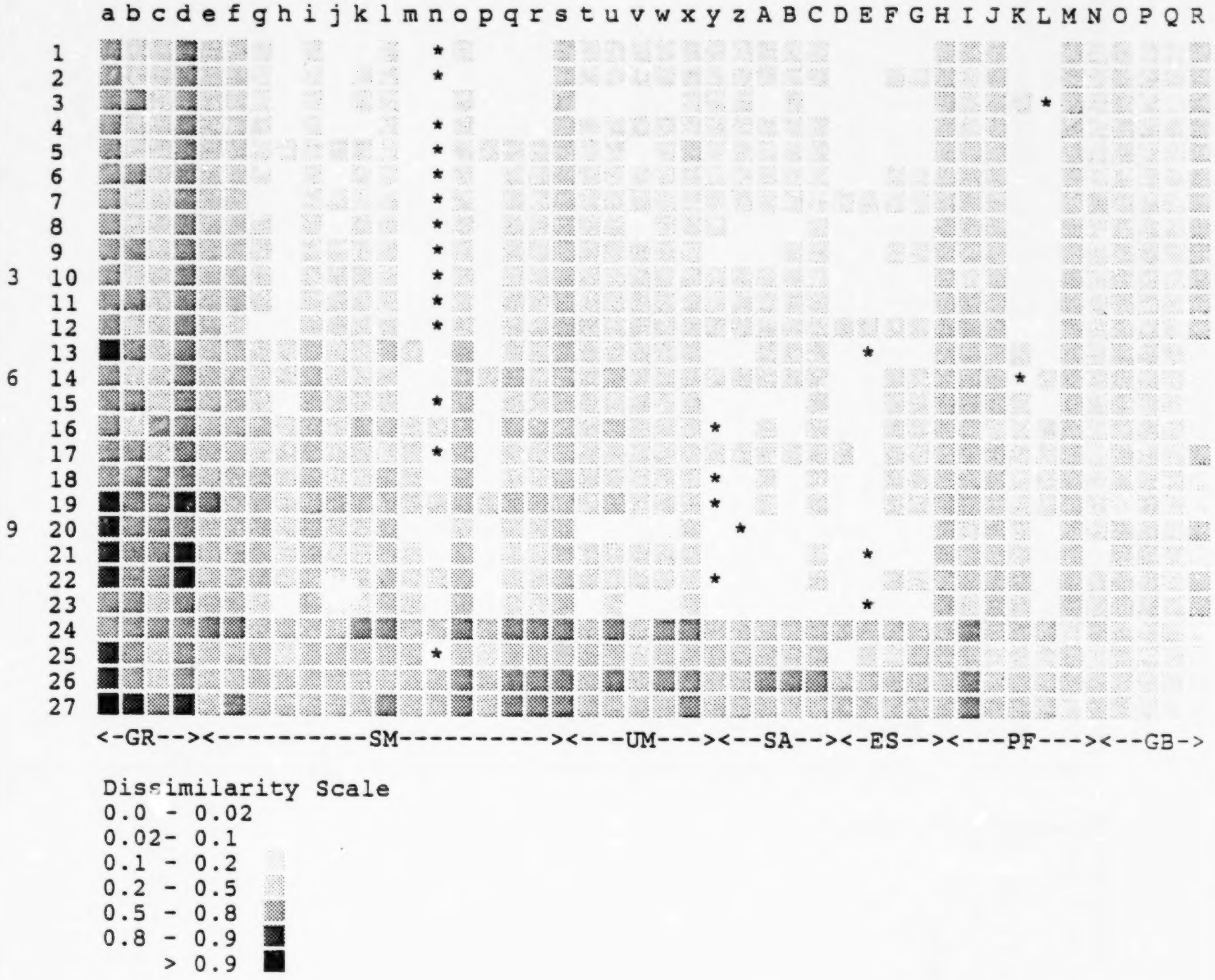

Figure 11. Dissimilarity diagram comparing Starkweather Pond pollen samples with 44 modern pollen samples. Asterisks mark the most-similar modern samples. Numbers on extreme left refer to ages of the samples (3, 6, and 9,000 yr B.P.). GR = oak grassland, SM = Dierra Montane Forest, UM = Upper Montane Forest, SA = subalpine, ES = eastern subalpine, PF = pine forest, and GB = Great Basin Steppe.

Horizontal Axis = Modern Pollen Samples Sierra Nevada
Vertical Axis = Starkweather Pond Madera Co. CA

Davis

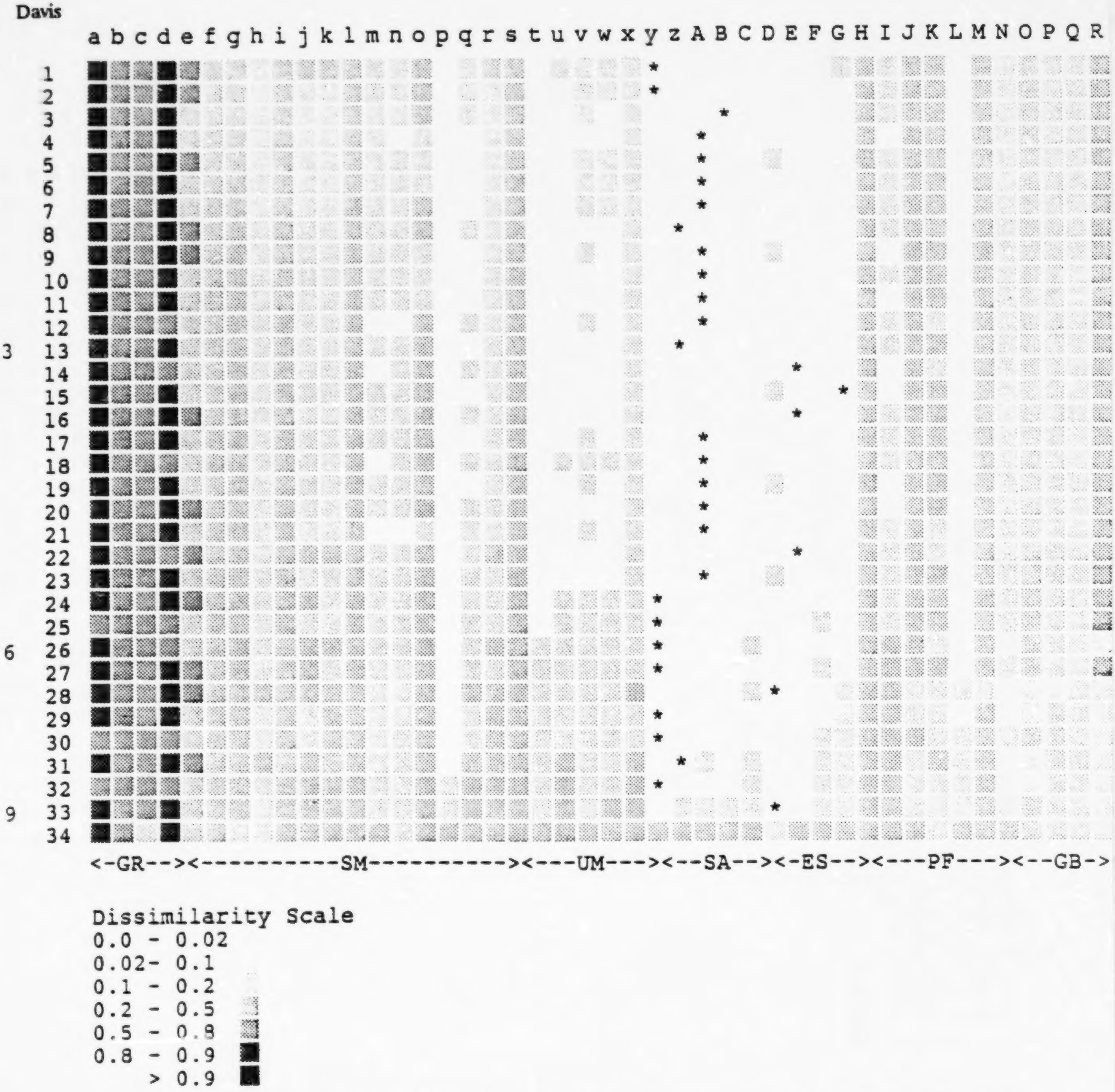

Figure 12. Dissimilarity diagram comparing Tioga Pass Pond pollen samples with 44 modern pollen samples. Asterisks mark the most-similar modern samples. Numbers on extreme left refer to ages of the samples (3, 6, and 9,000 yr B.P.). GR = oak grassland, SM = Sierra Montane Forest, UM = Upper Montane Forest, SA = subalpine, ES = eastern subalpine, PF = pine forest, and GB = Great Basin Steppe.

Horizontal Axis = Modern Pollen Samples Sierra Nevada
Vertical Axis = Tioga Pass Pond Mono Co. CA

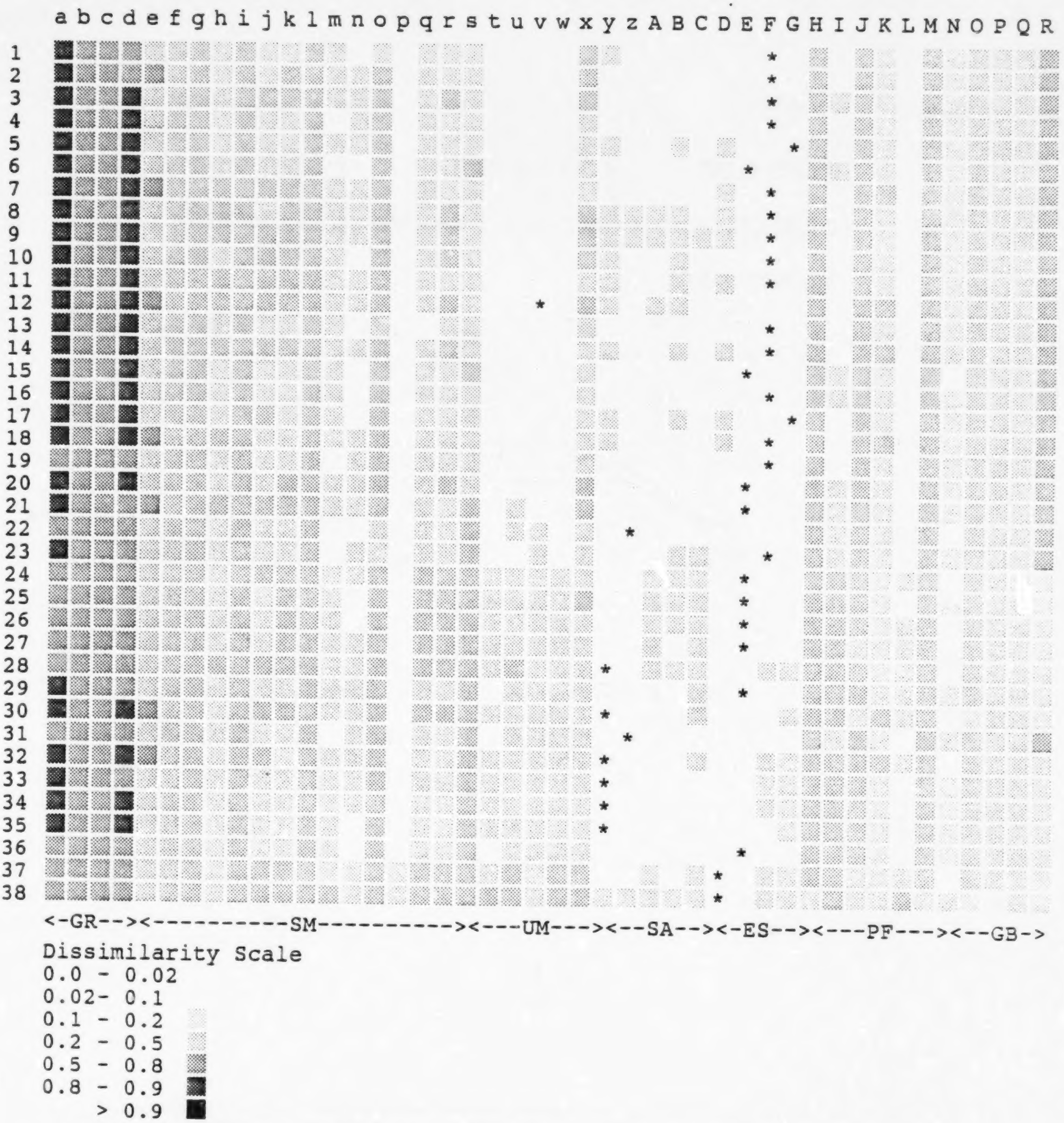

Figure 13. Dissimilarity diagram comparing Barrett Lake pollen samples with 44 modern pollen samples. Asterisks mark the most-similar modern samples. Numbers on extreme left refer to ages of the samples (3, 6, and 12,000 yr B.P.). GR = oak grassland, SM = Sierra Montane Forest, UM = Upper Montane Forest, SA = subalpine, ES = eastern subalpine, PF = pine forest, and GB = Great Basin Steppe.

Horizontal Axis = Modern Pollen Samples Sierra Nevada
Vertical Axis = Barrett Lake Mono Co. CA

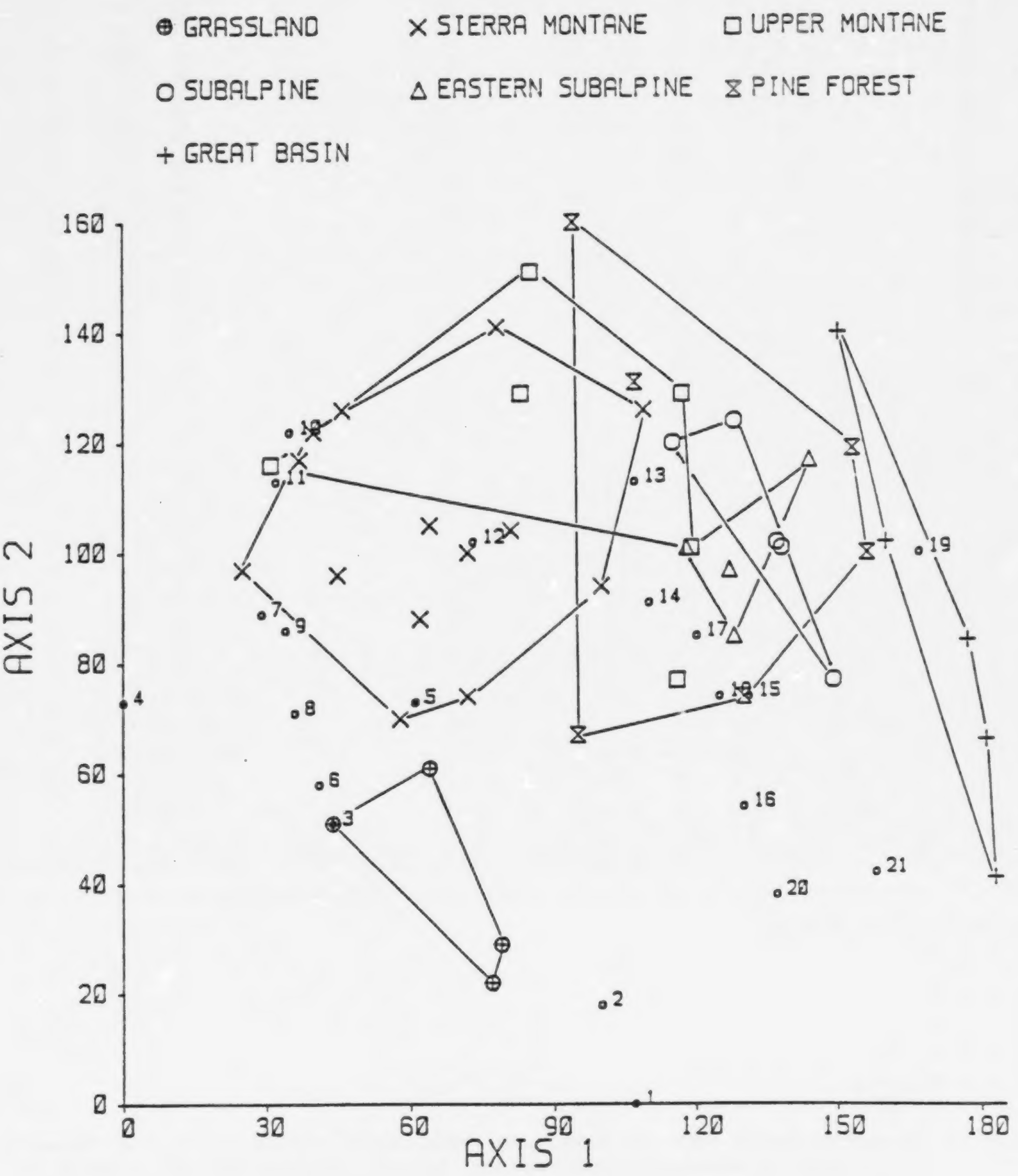

Figure 14. Detrended correspondence analysis of the modern set of 44 samples combined with the set of 21 samples collected by Adam (1967).

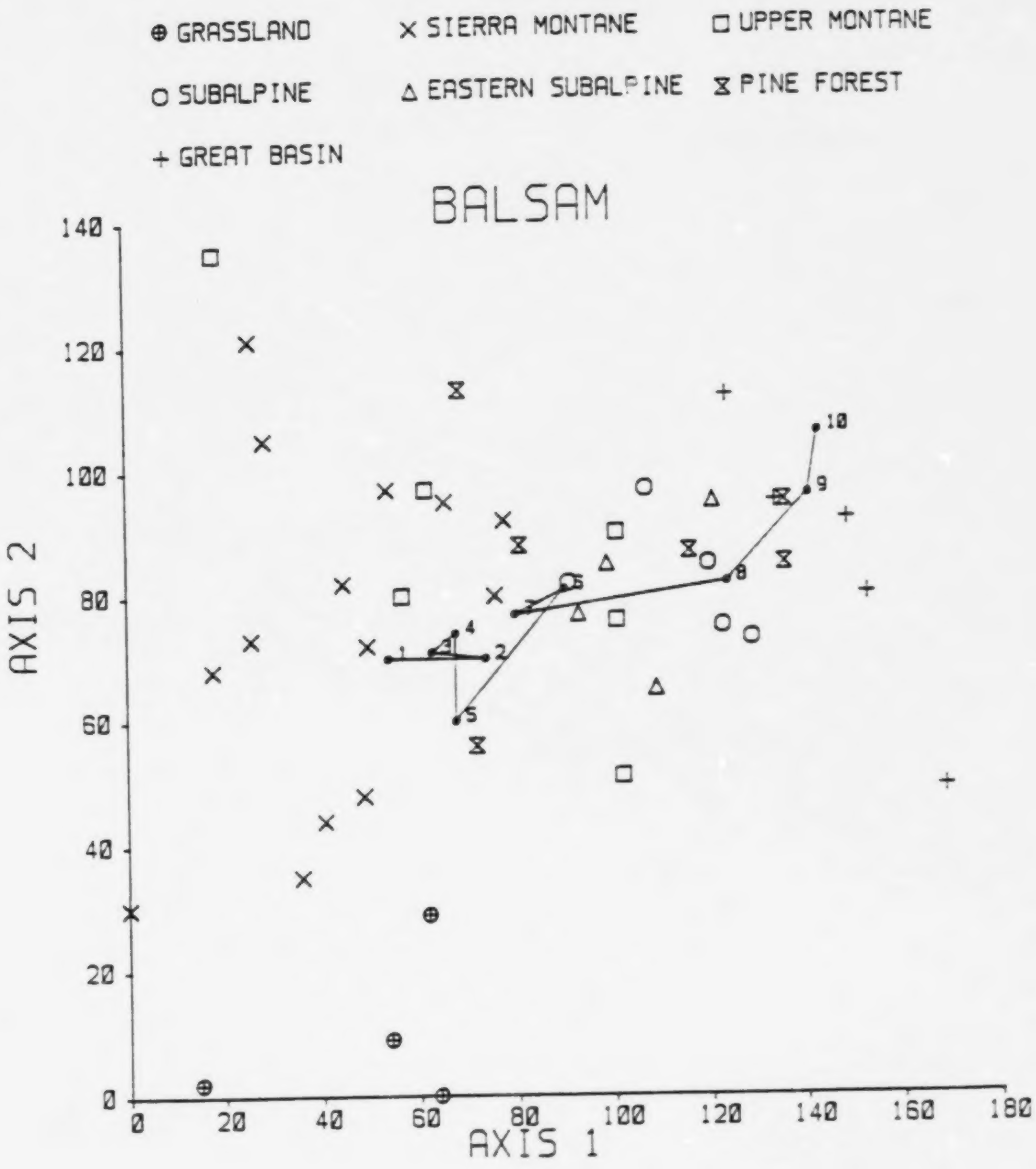

Figure 15. Detrended correspondence analysis of Balsam Meadow and modern samples, 1,000-yr averages plotted for fossil samples.

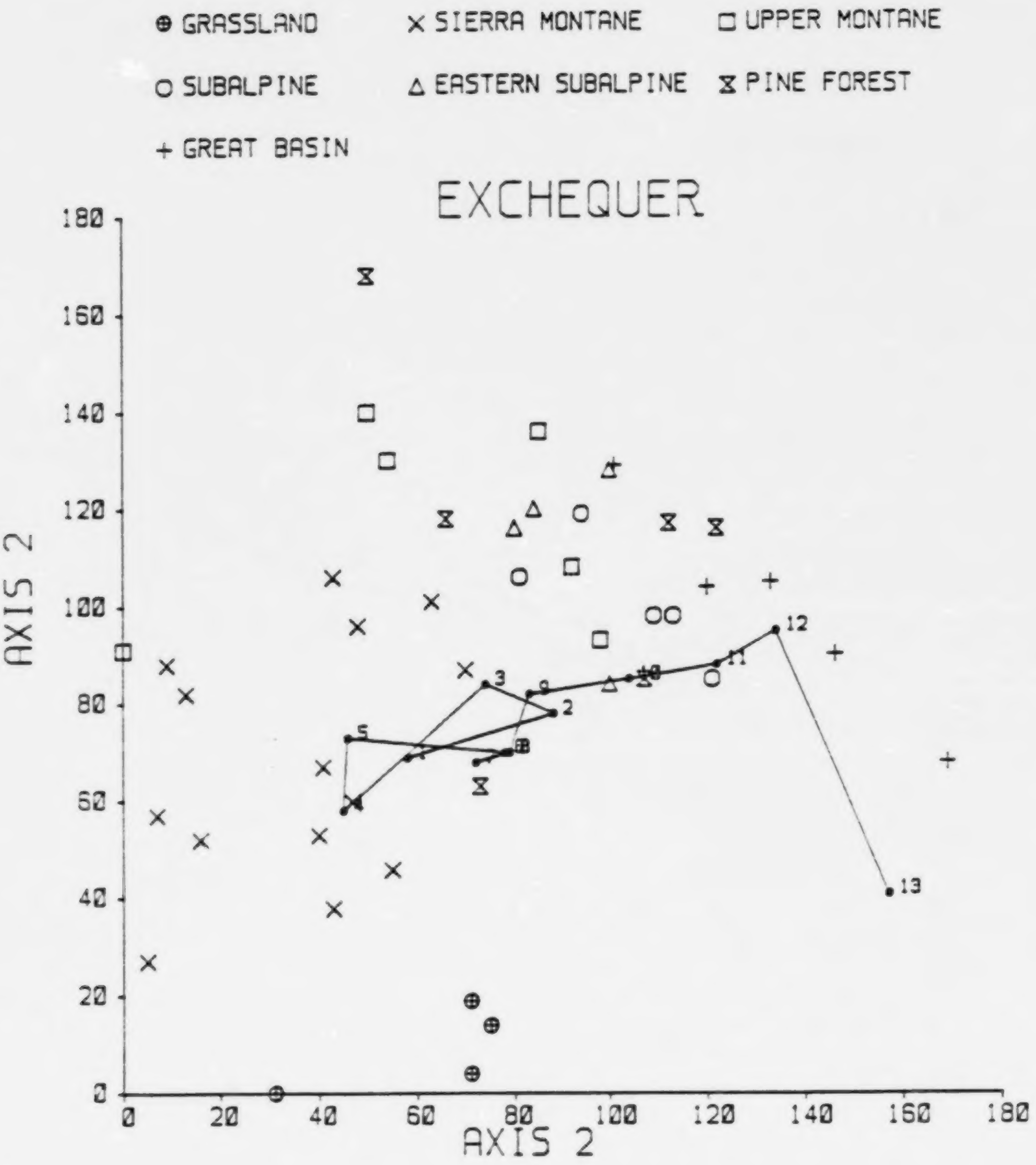

Figure 16. Detrended correspondence analysis of Exchequer Meadow and modern samples, 1,000-yr averages plotted for fossil samples.

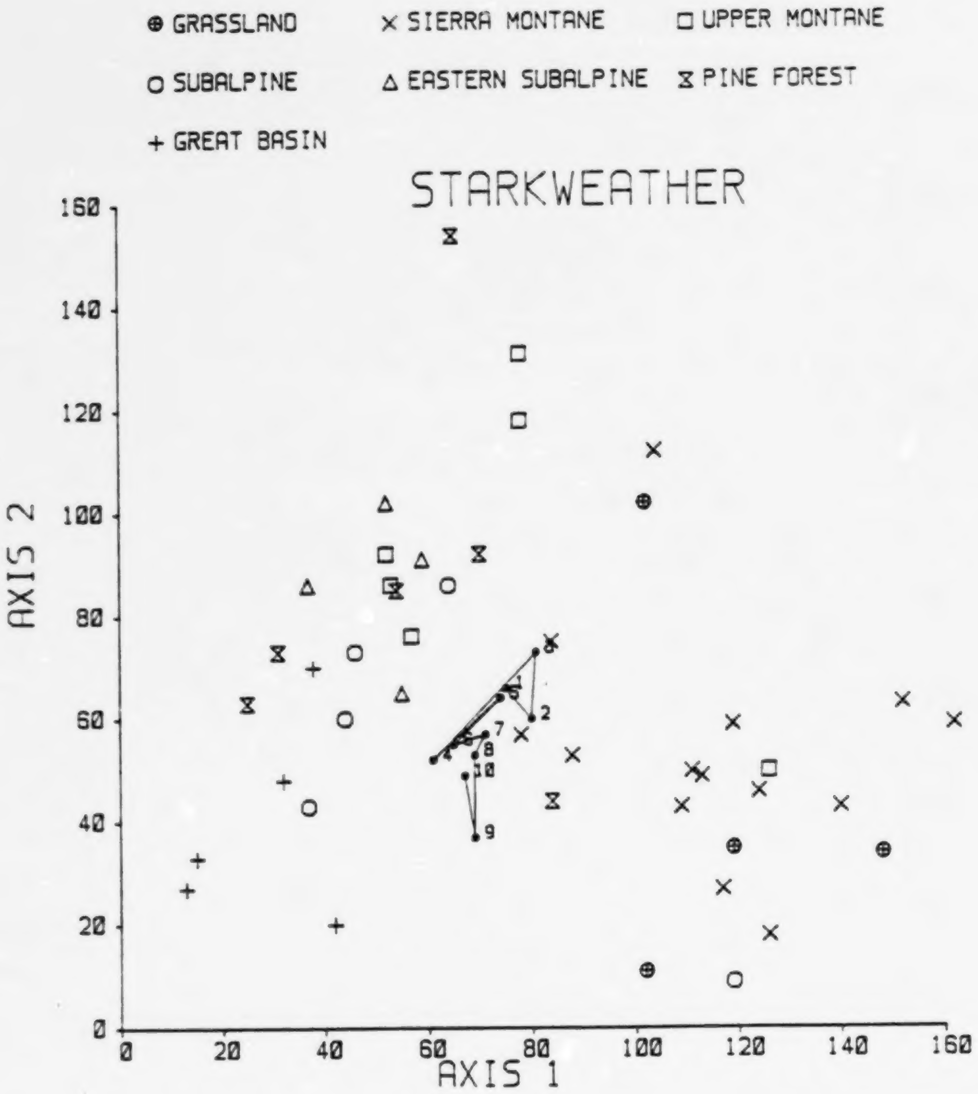

Figure 17. Detrended correspondence analysis of Starkweather Pond and modern samples, 1,000-yr averages plotted for fossil samples.

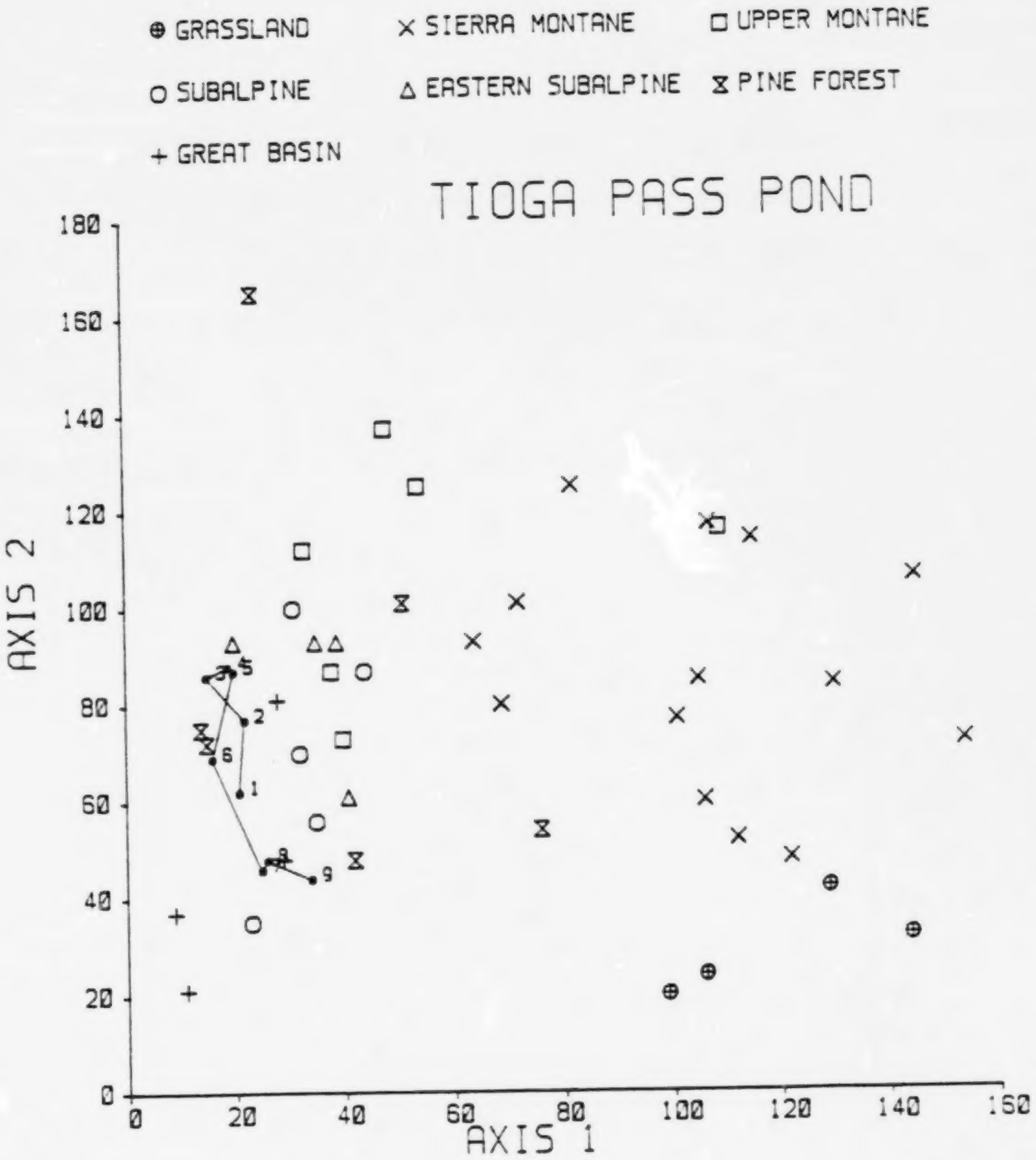

Figure 18. Detrended correspondence analysis of Tioga Pass Pond and modern samples, 1,000-yr averages plotted for fossil samples.

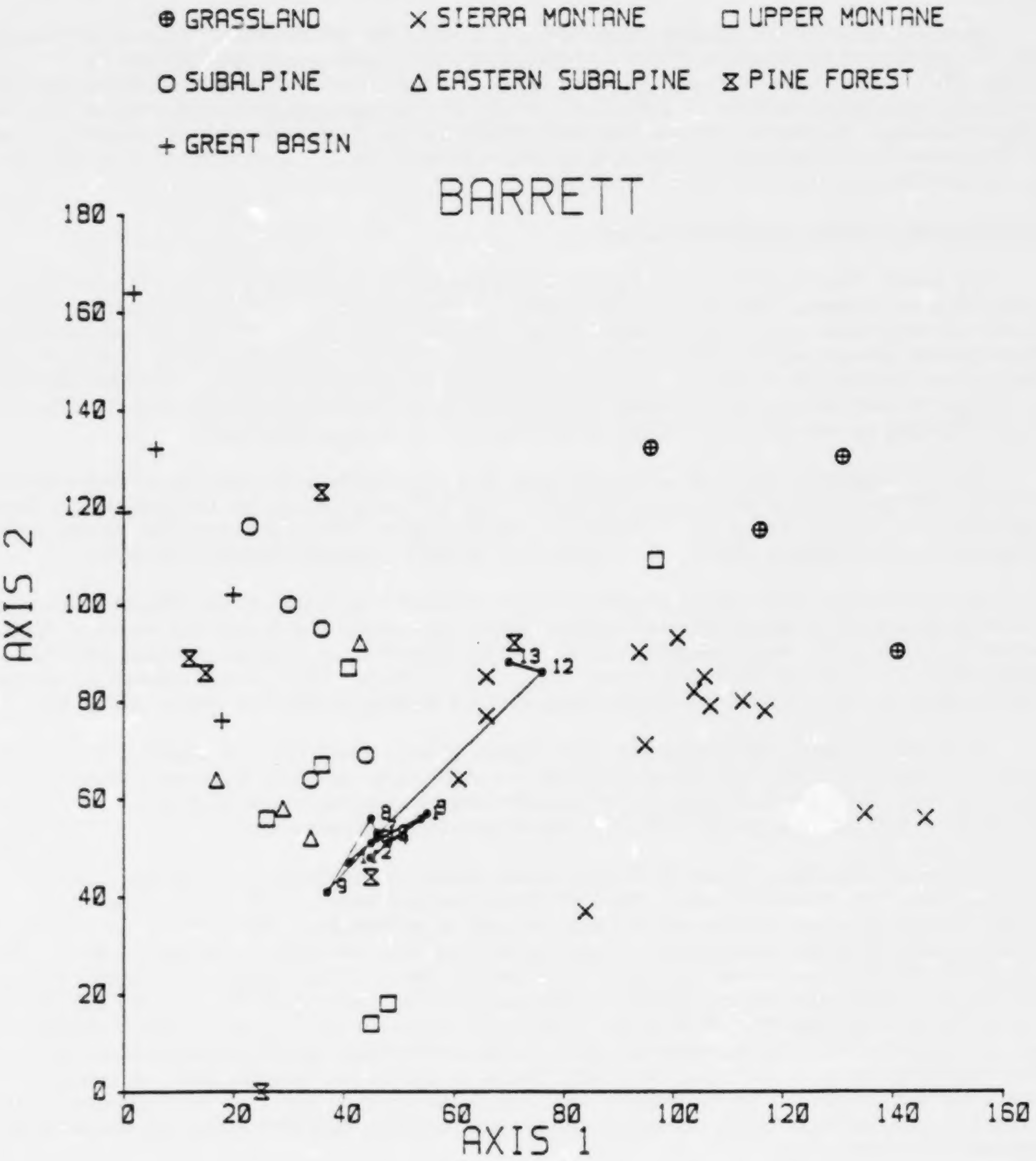

Figure 19. Detrended correspondence analysis of Barrett Lake and modern samples, 1,000-yr averages plotted for fossil samples.

first axis is a moisture ordination from wet (western Sierra) to dry (eastern Sierra) and the second axis is a temperature ordination from warm (low elevation) to cold (high elevation). The boundary between SM + UM samples versus SA + ES + PF is taken as a boundary between eastern and western Sierra Nevada types.

Most of Adam's (1967) Tioga Pass samples fall near or within the clusters formed by the modern samples set. The positions of the six outliers (Figure 14) result from their unusual percentages (compare Figure 1 with Adam, 1967). Sample 1 has very low Pinus percentages, 2 has high Other Compositae percentages, and 4 has very high Castanopsis percentages. Samples 16, 20, and 21 have high Artemisia percentages combined with low Pinus percentages, the distance between these three samples and the groups is less than for samples 1, 2, and 4. This comparison is a guideline for evaluating the fossil sequences. Samples as far removed as the six outliers do not have close analogs in the modern vegetation.

DCA of Fossil Averages and Modern Analogs

The Balsam Meadow 1000-year averages of fossil samples form a diagonal line from the upper right to lower left of the diagram (Figure 15), implying progressively greater moisture (eastern Sierra analog to western Sierra) and temperature (high to low elevation analog). The 8000- to 10,000-yr averages plot with the eastern Sierra modern analogs, and the 5000- to 1000-yr averages plot with western Sierra analogs. The convergent pattern formed by the 5000- to 1000-yr averages implies relatively small vegetation change. The 7000- and 6000-yr averages are near the east-west transition. The modern samples form a pattern similar to that of Figure 14 -- axis 1 forming an west (left) to east (right) ordination, axis 2 an elevational ordination.

The DCA diagram for Exchequer Meadow (Figure 16) shows a similar pattern, but the east-west transition is between 9000 and 10,000 yr B.P., with the millennium averages plotting closer to low-elevation, western Sierra vegetation from 12,000 to 5000 yr B.P. Thereafter, the trend reverses. The earliest vegetation recorded in the Exchequer Meadow diagram (Figure 12) is missing from the Balsam Meadow diagram (Figure 11).

The Starkweather Pond analysis (Figure 17) shows relatively little change in the millennium averages. The fossil samples plot along the east-west transition, so there is no evidence for an east-west transition. Higher values on axis 2 imply increasing similarity to high-elevation vegetation, i.e., progressive cooling from 9000 to 3000 yr B.P. The trends for Starkweather Pond (Figure 17) are similar. There is weak evidence for an east-west transition on axis 1, and the upward movement on axis 2 implying cooling from 9000 to 3000 yr B.P.

The polarity of axes 1 and 2 for Barrett Lake (Figure 18) are opposite those for Balsam and Exchequer Meadows (Figures 15 & 16). Low-elevation samples plot at the top of the figure, and western Sierra samples plot at the right. Relatively little change is apparent in the millennium averages after 12,000 yr B.P. The 12,000- and 13,000-yr B.P. averages plot far to the right, with western Sierra modern analogs.

The western Sierra sites (Figures 15-18) show similar chronologies of change but conflicting "temperature" histories. Early Holocene trends reverse after 5000 (Balsam and Exchequer) to 3000 yr B.P. (Starkweather and Tioga Pass Pond), roughly contemporaneous with the onset of the Neoglacial (Wood, 1975). The ambiguity probably results from my interpretation of axis 2 as an elevational, and hence temperature gradient. The relationship between elevation and axis-2 score is not perfect (Figure 14), and elevation is a complex gradient involving both temperature and precipitation. I have interpreted the mathematical derivation of DECORANA axes to prevent correlation (Hill, 1979) as an indication that moisture is not important to axis 2, because it is clearly important to axis 1, the west-east axis. However, this interpretation may fail for Starkweather and Tioga Pass Pond (Figures 17 & 18), which show little change on axis 1, the "moisture axis." A parsimonious interpretation is that axis 2 of the Starkweather and Tioga DCAs shows the same environmental history as axis 1 of Balsam and Exchequer DCAs; that is, increasingly mesic vegetation until 3000-5000 yr B.P. and more xeric vegetation thereafter.

Given the uncertainty resulting from the conflicting interpretations of the DCA results for the western Sierra sites, the pattern of millennial averages from 12,000 to 9000 yr B.P. at Barrett Lake (Figure 19) may represent a trend toward more xeric vegetation, cooler temperatures, or both.

CHAPTER 4

INTERPRETATION OF RESULTS

Dissimilarity analysis and DCA provide complementary scenarios of vegetation change in the central Sierra Nevada. Prior to ca. 9000 yr B.P., the vegetation of the western Sierra Nevada resembled that found east of the Sierra crest today, by 6000 yr B.P. modern vegetation patterns had become established. The trend toward decreasing aridity which began in the early Holocene continued until 5000 to 3000 yr B.P., when the direction reversed. The two techniques differ in particulars, but the direction and magnitude of the vegetation change are consistent. The 9000-yr B.P. analog betokens xeric vegetation in the western Sierra; the 6000-yr B.P. analog indicates vegetation similar to today.

DCA analysis is useful for showing overall trends of vegetation change, whereas dissimilarity analysis provides specific modern analogs, albeit with occasional misclassification. Tables 2 and 3 compare the results of the two techniques. In Table 3, the Euclidian distance between millennium averages was calculated as a measure of "greatest change" for DCA. For dissimilarity analysis, the number of samples in the transect was used as a measure of change. DCA indicates an earlier east-west transition than dissimilarity analysis for Balsam Meadow, later at Exchequer Meadow, and inconclusive results at Starkweather, Tioga, and Barrett. The east-west transition is the greatest change recorded at Balsam, Exchequer, and Tioga, but the end of the ice age produced greater change at Starkweather and Barrett (Table 3).

Since the goal of the analyses is to use an ancient analog to estimate the potential effects of greenhouse warming, it appropriate to compare the results of this study with those produced by the GISS and OSU climate models. Climate estimates are calculated for fossil samples with good modern analogs (<0.1 dissimilarity; Figures 9-13). Annual precipitation and mean annual temperature is calculated from lapse rates calculated by Rourke (1988). The data set includes 44 stations from central California ranging from 7 m to 3231 m elevation. The lapse rates for the eastern Sierra Nevada are 181.6 mm^{-km} and -5.36°C km^{-1}, and 683.7 mm^{-km} and -4.93°C km^{-1} Five-level Gaussian smoothing was performed to remove effects of extreme values (Table 4). Ordinarily, the elevational-analog technique produces negatively correlated temperature and precipitation reconstructions, but the east and west slopes of the Sierra Nevada have different lapse. Because lowest dissimilarity can switch from one slope to another, changes in temperature and precipitation are not necessarily correlated.

The western Sierra samples are discussed separately from Barrett Lake due to their mutual similarity and their differences from the Barrett Lake climatic reconstruction. During the 6000-yr B.P. analog, mean annual temperature is cooler than modern in three of the four western Sierra sites, and unchanged in the third. Annual precipitation is greater than modern in two sites but less in the other two. During the 9000-yr B.P. analog, temperature is lower in three sites, but greater in the third. Precipitation is greatly reduced (by over 50% !) in three of the four sites, and slightly reduced in the third (Table 4). The combined history is of relatively little change 6000 yr B.P., but of much more xeric vegetation 9000 yr B.P.

The xeric character of the early Holocene vegetation is supported by pollen accumulation rates (Davis, 1984, 1987). In the Pinus stratigraphic Zone (after ca. 7000 yr B.P.), the pine pollen influx at Balsam and Dinkey Meadows is over 15,000 grains $\mathrm{cm}^{-2}\ \mathrm{yr}^{-1}$ and fir pollen influx is over 2000 grains $\mathrm{cm}^{-2}\ \mathrm{yr}^{-1}$. Earlier, in the Artemisia zone, the rate for pine is less than 9000 grains $\mathrm{cm}^{-2}\ \mathrm{yr}^{-1}$, and for fir it is less than 600 grains $\mathrm{cm}^{-2}\ \mathrm{yr}^{-1}$.

During the early Holocene and late glacial, the climate at Barrett Lake was markedly different from that of the western Sierra sites. During the 6000-yr B.P. analog, annual temperature was slightly reduced and annual precipitation was the same as modern. During the 9000-ya analog, temperature was lower than during the 6000-yr B.P. analog, and precipitation was increased nearly threefold. An early-Holocene precipitation increase is supported by reconstructions of climate for the Mojave Desert east of the Sierra Nevada (Spaulding and Graumlich, 1986). A trans-Sierra contrast of climatic history has been suggested by Davis and Sellers (1987).

Table 2. Modern Analogs for Past Vegetation

Site & Age	Dissim. Analysis	DCA
Balsam Meadow		
0K	Sierra Montane	Sierra Montane
3K	Sierra Montane	Sierra Montane
6K	Upper Montane	Eastern Subalpine
9K	Pine Forest	Pine Forest
Exchequer Meadow		
0K	Sierra Montane	Sierra Montane
3K	Sierra Montane	Sierra Montane
6K	Sierra Montane	Sierra Montane
9K	(Pine Forest)	Sierra Montane
12K	(Pine Forest)	Great Basin
Starkweather Pond		
0K	Sierra Montane	Sierra Montane
3K	Sierra Montane	Sierra Montane
6K	Pine Forest	Sierra Montane
9K	Subalpine	Pine Forest
Tioga Pass Pond		
0K	Subalpine	Subalpine
3K	Subalpine	Eastern Subalpine
6K	Subalpine	Eastern Subalpine
9K	Eastern Subalpine	Subalpine
Barret Lake		
0K	Eastern Subalpine	Pine Forest
3K	Eastern Subalpine	Pine Forest
6K	Eastern Subalpine	Pine Forest
9K	Subalpine	Pine Forest
12K	Subalpine	Sierra Montane

Table 3. Timing of Vegetation Change

Site	Dissim. Analysis	DCA
Balsam Meadow		
East-West Transition	9K	8K
Greatest Change	9K	9K
Exchequer Meadow		
East-West Transition	9K	10K
Greatest Change	9K	11K
Starkweather Pond		
East-West Transition	9K	9K
Greatest Change	(3K)	3K
Tioga Pass Pond		
East-West Transition	--	--
Greatest Change	--	7K
Barrett Lake		
East-West Transition	--	12K
Greatest Change	--	12K

Table 4. Temperature and Precipitation Estimates

Site	Temperature (C)	Precipitation (cm/yr)
Balsam Meadow		
0K	8	119
3K	6	128
6K	4	138
9K	6	45
Exchequer Meadow		
0K	8	119
3K	5	136
6K	5	138
9K	7	44
Starkweather Pond		
0K	6	137
3K	6	137
6K	5	114
9K	3	135
Tioga Pass Pond		
0K	3	163
3K	4	94
6K	3	155
9K	5	50
Barret Lake		
0K	6	48
3K	5	48
6K	5	48
9K	3	135
12K	3	127

The GISS and OSU climatic models for $2xCO_2$ do not closely match either historic analog. They predict increased temperature (2-4°C) and reduced precipitation (15-25 mm yr^{-1}) for the grid points closest to the western Sierra. Both historic analogs call for reduced temperatures in the western Sierra, and the 9000-yr B.P. analog calls for a much greater reduction in precipitation (ave. 65 mm yr^{-1}) than do the $2xCO_2$ models.

The models provide conflicting precipitation reconstructions for the eastern Sierra. The GISS grid point closest to the eastern Sierra (31.30N 35.22N x 110W) predicts an increase of 51 mm yr^{-1} for $2xCO_2$, but the OSU model indicates a 77 mm yr^{-1} decrease for its 32-34N x 115W grid point. Because the 6000-yr B.P. analog for the eastern Sierra indicates little change, it differs from both models. The 9000-yr B.P. analog agrees with the GISS, but not with the OSU model. Both models indicate temperature increases for $2xCO_2$ (5°C for GISS, 3°C for OSU), but both analogs indicate lower temperature.

The GISS model predicts reduced precipitation west of the Sierra Nevada and increased precipitation to the east, but the overall correspondence between the ancient analog and computer model is poor due to the analog's indications of lower temperature 9000 yr B.P. Some of the differences may reflect nonclimatic differences between the early-Holocene environment and that of today. In particular, the soils would have shown the effects of glacial and periglacial action, and would have contained less organic matter and lower nitrogen. Soil moisture-holding capacity should have been less, reinforcing the effects of lower precipitation. In addition, the coarseness of the grid points of the GCMs is simply too great to represent opposite sides of the Sierra crest.

UNCERTAINTIES

The techniques used herein are subject to several constraints. The vegetation reconstructions based on pollen analysis are most reliable if analogs exist in the modern vegetation. The reconstructions are based only on close (<0.1 dissimilarity) matches for dissimilarity analysis, but the technique produces frequent misclassifications (Figure 8). DCA does not provide an index of the precision of the match. Despite these uncertainties, there is good general agreement of the timing and direction of vegetation change among the four western Sierra sites.

The reconstructions for the eastern Sierra are less certain because only one site has been studied. However, the environmental sequence for Barrett Lake matches that of the desert east of the Sierra Nevada (Spaulding and Graumlich, 1986). Additional sites at high and mid-elevation should be studied on the eastern slope of the Sierra Nevada to confirm the Barrett Lake record and provide better coverage (Figure 20).

More disturbing is the disagreement between the temperature sequence resulting from numerical analyses and estimates based on the elevational distribution of indicator taxa at Exchequer Meadow (Davis and Moratto, 1988). The presence of Sequoiadendron pollen Juniperus or Calocedrus macrofossils in early Holocene sediment from Exchequer meadow indicates that temperatures were no colder than today. Both Sequoiadendron and Calocedrus would be near their upper elevational limit at Exchequer Meadow (2219 m), and neither is present there today. For these species to have been present near their current upper-elevational limits, temperatures could not have been much colder than today.

Both numerical techniques indicate lower temperatures during the early Holocene. The closest modern analogs indicated by dissimilarity analysis are samples taken near timberline or in pine forest (Figures 9-12), and the early-Holocene millennium averages plot near high-elevation samples on the DCA axes (Figures 15-18). Since the numerical techniques are based on the analog technique, they could fail if the early-Holocene vegetations have no modern analog. At Barrett Lake and Starkweather Pond, the few Pinus macrofossils preserved in early-Holocene sediment are of P. monticola, P. murrayana, and P. flexilis (Anderson, 1987). These are not the species prominent in the modern pine forest of the eastern Sierra (P. jeffreyi and P. ponderosa are), so a modern forest may be a poor analog for the early Holocene pine forest at mid- to high elevation. However, P. murrayana and P. flexilis are timberline species, so their presence supports an interpretation of lower temperature during the Early Holocene.

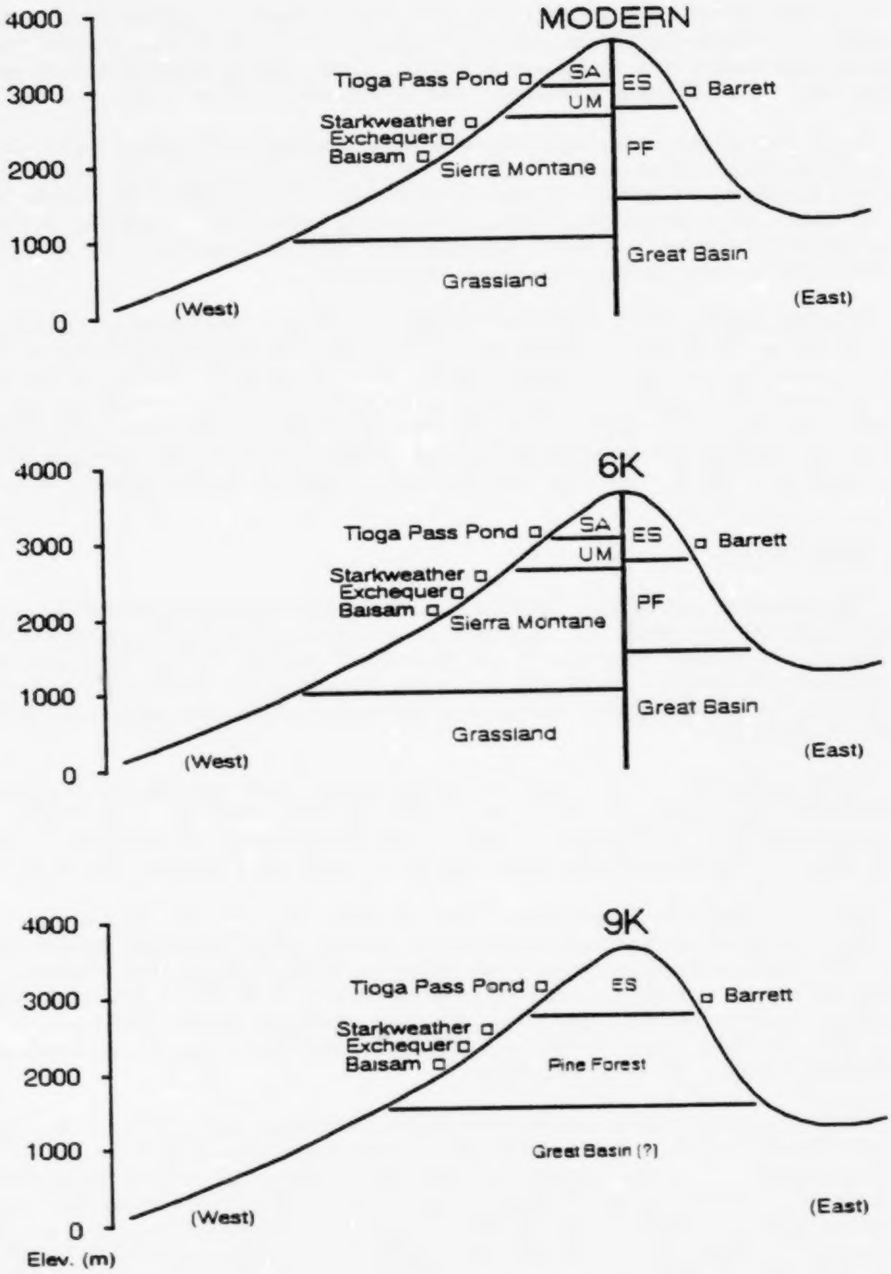
MODERN
6K
9K
4000
3000
2000
1000
0
Elev. (m)
Tioga Pass Pond
Starkweather
Exchequer
Balsam
Barrett
SA
ES
UM
PF
Sierra Montane
Great Basin
Grassland
Pine Forest
Great Basin (?)
(West)
(East)

Figure 20. Vegetation zonation in the central Sierra Nevada, 6,000 ya (6k) and 9,000 ya (9k) reconstructions based on DCA and DA.

Given the conflict between the interpretations, it seems best to conclude that the early-Holocene temperature record is uncertain. However, the interpretation of early-Holocene aridity in the western Sierra is supported by the numerical analysis and the macrofossil abundances (Davis et al., 1985; Davis and Moratto, 1988, Anderson, 1987). It has been suggested that the presence of Sequoiadendron pollen at Exchequer Meadow is inconsistent with greater aridity. Rundel (1972) has demonstrated that soil moisture is greater within Sequoiadendron groves than beyond the grove boundaries. However, this variable affects the distribution of Sequoiadendron at the community scale, and not at larger biogeographic scales. Factors other than soil moisture must determine to elevational and aerial distribution of Sequoiadendron groves, because sites with sufficient soil moisture but without Sequoiadendron exist both within the plants' range and beyond it. The Sequoiadendron pollen at Exchequer meadow indicates that soil moisture was sufficient to support a grove, a conclusion made obvious by the presence of sedge pollen in the sediment (Davis and Moratto, 1988)

A more general uncertainty concerns the time period chosen as an analog for greenhouse warming. Typically, the middle Holocene (ca. 6000 yr B.P.) is used because it has been traditionally thought to be a period of higher temperature (Deevey and Flint, 1957). The reasons for considering an early-Holocene analog (9000 yr B.P.) for California are outlined in the introduction to this paper. However, the numerical methods indicate that both 6000 and 9000 yr B.P. were colder than today. This contradicts the nearly universal prediction for the effects of greenhouse warming. Although the area may become drier due to greenhouse processes, the analog appears to have failed to show the effects of elevated temperature on the forests of the western Sierra Nevada.

Finally, the early-Holocene analog may not simulate the effects of rapid climatic change on the vegetation of the western Sierra Nevada. The rapidity with which climate may change between now and the next century could be without precedent. The processes of migration and ecological interaction that operate during climatic changes (Cole, 1985) may be too slow to produce the types of communities that existed during the ancient climatic analogs for greenhouse warming. The rapidity of greenhouse-induced climatic change may produce biotic communities for which there is no ancient analog.

CHAPTER 5

IMPLICATIONS OF RESULTS

ENVIRONMENTAL IMPLICATIONS

The implications of the results differ for the two analogs. The 6,000-yr B.P. analog implies relatively little change. However, during the 9,000-yr B.P. analog, the forests of the western Sierra resembled those currently found in the eastern Sierra (Figure 20). Xeric vegetation surrounded the fossil sites that now are in mesic Sierra montane forest, and the pollen of lumber-producing pines and firs was less plentiful. Some trees endemic to the central Sierra were more widespread than today. Giant sequoia pollen was common during the early-Holocene at Exchequer Meadow (Davis and Moratto, 1988) and near Boyden Cave (Cole, 1983) where none is present today. Six thousand years ago the vegetation zones were similar to those of today, but 9,000-yr B.P. trans-Sierran biotic differences were less pronounced.

We have no fossil sites at low elevation, but the abundance of Ericaceae pollen at the base of the Balsam and Exchequer diagrams (Figures 3 & 4) may indicate that chaparral vegetation was much more extensive 9,000 ya. Fire frequency could have been greater than today, but the abundance of charcoal in the sediments is less at low elevation (Davis et al., 1985; Davis and Moratto, 1988). However, the charcoal abundance probably reflects the lower fuel load and, hence, charcoal production in the early-Holocene vegetation rather than lower fire frequency.

SOCIOECONOMIC IMPLICATIONS

Forest changes in the direction and magnitude of those seen during the 9000-yr B.P. analog would have dramatic effects on tourism and the lumber industry. Quantitative estimates are not possible with the kinds of data presented here, but the total area occupied by forest was perhaps half that of today. This figure is consistent with the pollen accumulation rates cited in the "Interpretation of Results." Most of the important lumber species were probably present in lower numbers, but groves of giant sequoia and incense cedar may have been more widespread.

The open character of the vegetation might be less scenic for tourists, but reduced tourism would be unlikely if temperatures were higher. The relatively cool mountains would be very attractive. Supplying water to the increased tourist population would be more difficult due to reduced precipitation.

The negative effects of climate change on the western Sierra could be offset by increased precipitation and forest density for the eastern Sierra, but the geography of the mountain range reduces the compensation. The gentle western slope occupies far greater area than the eastern slope. A doubling of the area occupied by forest on the east slope produces far less change than corresponding reduction on the west slope. Also, the eastern slope is farther from population centers and receives less tourist visitation.

The goal of this research is to document the effects of elevated temperature on the forests of the western Sierra Nevada. However, the east-west climatic contrast has important implications for water supply. Increased runoff for the east slope could offset the reductions in water supply to urban areas due to greater aridity for the western slope. The implications are interesting, but the projected increased is based on just one fossil site.

CHAPTER 6

POLICY IMPLICATIONS

Three issues resulting from climatic change in the central Sierra Nevada must be addressed. Reduced timber production will result in lost revenue. The reduction appears unavoidable if climate changes during the next century are in the direction and magnitude of those during the 9000-yr B.P. analog. Decreased precipitation could result in greater tourist pressure at time the ecosystem is less able to withstand it. It may become necessary to regulate the numbers of tourists throughout the Sierra Nevada. Reduced precipitation in the western Sierra has implications for reclamation programs. If precipitation increases in the eastern Sierra, the greater demand for water west of the Sierra Nevada would increase the value of aqueducts originating east of the crest.

LIST OF ABBREVIATIONS

CCM	Community Climate Model
DCA	Detrended Correspondence Analysis
Holocene	the last 10,000 years, = postglacial
NCAR	National Center for Atmospheric Research
ppm	parts per million
yr B.P.	calculated radiocarbon age Before Present
ya	calendar years before present

PLANT NAMES

Abies	fir
Alnus	alder
Ambrosia	ragweed
Arceuthobium	dwarf mistletoe
Artemisia	sagebrush and wormwood
Castanopsis	chinquapin
Cercocarpus	mountain mahogany
Cheno/Am	chenopod family and amaranth genus
Cupressaceae	(TCT) juniper, incense cedar, cypress, yew
Ericaceae	heath family, including manzanita
Gramineae	grass
Other Compos.	undif. members of the sunflower family
Pinus	pine
Quercus	oak
Sarcobatus	greasewood
Tsuga	hemlock

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HARD TIMES AHEAD FOR GREAT LAKES FORESTS: A CLIMATE THRESHOLD MODEL PREDICTS RESPONSES TO CO_2-INDUCED CLIMATE CHANGE

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FINDINGS[1]

Geographical distributions of four timber trees important in the Great Lakes region have been predicted assuming CO_2 doubling by 2090 A.D., and using climate scenarios developed by the GISS and GFDL models. The climate threshold model used for these predictions assumes that a tree species will only grow within a climate-space identical to that within its present geographical range, and that species can colonize new regions at the rate of 100 km per century, a rate more than double the maximum ever recorded for temperate trees in the Quaternary paleorecord. Under GISS-predicted climate, the ranges of sugar maple (Acer saccharum), yellow birch (Betula allegheniensis), hemlock (Tsuga canadensis), and beech (Fagus grandifolia) contract markedly within the Great Lakes region. The marginal nature of the climate makes it likely that hemlock, yellow birch, and sugar maple will be much less abundant in those parts of Wisconsin and Michigan where they can still grow. Beech will be eliminated completely from the lower peninsula of Michigan, where it is presently abundant. The geographical ranges of all four species will be much reduced under the GISS scenario, although potentially suitable habitat will be created to the north in central Canada south of James Bay. In succeeding centuries, more of this region may eventually be colonized. Under GFDL-predicted climate, all four species will be eliminated entirely from the Great Lakes region, persisting only in Nova Scotia and northern New England. Larger potential ranges will exist in eastern Canada at the latitude of James Bay. This region might eventually be colonized from the southeast if trees can adapt to photoperiods at that latitude. Although the climate threshold model considers neither competition from other species nor soils, it provides the first prediction of forest response that takes geography and availability of seed source into account.

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CHAPTER 1

INTRODUCTION

Dominant commercially valuable trees in the hardwood forests of the Great Lakes region are hemlock (Tsuga canadensis L.), American beech (Fagus grandifolia Ehrh.), yellow birch (Betula allegheniensis Britton), and sugar maple (Acer saccharum Marsh.). All four species reach range limits within the Great Lakes region, and therefore populations in this region might be expected to react with sensitivity to climatic change. The question is, are the climatic changes expected with doubled CO_2 of such a nature that they will affect these species, and of such a magnitude that Great Lakes forests will be greatly altered?

In this report we have assembled evidence from the literature that demonstrates a functional relationship between climate and the geographical limits for each species' range. Many of the observations are anecdotal, however, and even experimental results cannot readily be translated into quantitative parameters that describe the environment at the species limit. Nevertheless, the review was valuable in pointing to the climatic variables that are important in reproduction, seedling establishment, and growth of each tree species in various parts of its geographical range. The climatic limits were then quantified through correlation of range limits with geographical distributions of climatic variables. Although in several cases there is ample evidence that extreme events actually limit the survival of trees, we were forced to correlate with averages because the General Circulation Model output does not include extreme events. Monthly isotherms do coincide with range limits in many cases, however, suggesting that they are statistically correlated, at least regionally, with the extreme events that limit tree growth.

The climatic conditions at a species' limit constitute threshold conditions for its survival. The thresholds that exist at the northern, western, and southern limits of yellow birch, hemlock, maple, and beech define a climate-space within which each species can grow, and outside of which it cannot. Once having defined this climate-space, we have inspected the predictions of General Circulation Models for climatic conditions under doubled CO_2 to determine where similar climate-spaces will be located. Because each species is limited by a different combination of climatic variables, the alteration of potential geographical habitat is different for each species.

We have then taken an additional step to predict where each species will actually be found, given the constraints of seed dispersal from existing populations. To do this, it is necessary to specify a time dimension; we have presumed that doubling of CO_2 in the atmosphere will be achieved by about 2090 A.D. Assuming a finite rate of range extension, based on rates of colonization of new regions recorded in pollen deposits during the Quaternary, we have predicted the areas of potential climate-space that one might reasonably expect to be occupied by each species by 2090 A.D.

CHAPTER 2

RESPONSES TO CLIMATE - A LITERATIVE REVIEW

Eastern Hemlock

Tsuga canadensis (L.) Carr., commonly known as eastern hemlock, is a shallow-rooted species, which reaches reproductive maturity between 20 and 40 years of age when growing under good conditions, and may live as long as 600 years (Fowells, 1965). Hemlock reaches the edge of its westernmost distribution in the Great Lakes region, and can be found growing in disjunct populations in Minnesota, Wisconsin, and Indiana, 50-70 km away from the edge of the continuous range. The outlying populations provide clues to the factors important at the species' range limit. Many of them grow in topographically unique areas, such as canyon walls, rims of deep ravines (Daubenmire, 1931; Friesner and Potzger, 1931), within steep ravines (Cundiff, 1949; Calcote, 1986), or on valley slopes (Adams and Loucks, 1971).

Furthermore, hemlock throughout its entire range is found more commonly on north-facing slopes: in North Carolina (Oosting and Hess, 1956), in Georgia (Bormann and Platt, 1958), in Ohio (Black and Mack, 1976), in New York, and in Ontario (Kavanagh and Kellman, 1986). North-facing slopes have characteristically lower air temperature, soil temperature, and vapor pressure deficit than south-facing slopes (Cantlon, 1953). North-facing slopes also have fewer temperature and moisture extremes, and considerably lower evaporation (Cooper, 1961). Hemlock also grows in ravines in other parts of its range, such as New York, where hemlock's shallow rooting system seems to be particularly adapted to steep, narrow ravines without much soil accumulation (Lewin, 1974).

In ravines with greater soil accumulation, hemlock grows on mid-slopes while oaks and white pine dominate the upper slopes (Lewin, 1974). Laboratory tests showed that photosynthetic efficiency of hemlock was 15% higher at temperatures characteristic of lower valley slopes than at temperatures characteristic of upper slopes. In the summer, when soil moisture reaches levels low enough to severely restrict photosynthetic capabilities, the cooler temperatures that result in higher photosynthetic efficiency become critical to the survival and growth of hemlock (Adams and Loucks, 1971).

In a comparison between populations of hemlock at the northern edge of the species' range and the center of the species' geographic range, Kavanagh and Kellman (1986) found that there was little difference between long-term growth at the northern edge versus the center of the range, but at the northern edge of the range, there seemed to be little recruitment after the initial establishment of the populations. Hemlock made up fewer than 5% of saplings at northern sites. An exception to this observation was at dry sites, where 30% of the seedlings and saplings present were hemlock.

Hemlock seeds from the northern edge of the species' range germinate optimally between 12° and 17°C after 10 weeks of moist stratification (Stearns and Olson, 1958). In the field, seeds germinate and grow best on moist mineral soil, moss beds, or rotting logs. Seedlings are very sensitive to water stress; therefore, shaded conditions reduce the risk of desiccation (Olson, et al., 1959). The cooler, moister habitats of north-facing slopes and steep ravines seem to be optimal habitat for hemlock regeneration.

Kavanagh and Kellman (1986) suggest that the limitation of successful establishment of hemlock to drier sites at the northern edge of its range could be a result of competition with more mesic species, such as sugar maple, striped maple, beech, and balsam fir. The cooler, drier sites which favor the establishment of eastern hemlock could be the sites where competing species exhibit slower growth rates.

This same idea was advanced earlier by Daubenmire (1931) as an explanation for the persistence of hemlock in Indiana on soils with lower moisture content than the soils of the adjacent beech-maple stands. He argued that hemlock was limited to the least favorable sites because of an inability to grow with superior competitors on the more favorable sites.

Ability of hemlock seeds to germinate and grow on drier sites may be explained by the existence of two physiological races of hemlock in Wisconsin, one growing in the northeastern corner of the state, which is characterized by cooler, moister conditions, and the other in southwestern Wisconsin. Seedings grown from seeds collected in southwestern Wisconsin had higher water-use efficiency, and higher absolute CO_2 uptake, especially at low levels of irradiance (Eickmeier, et al., 1975).

American Beech

Fagus grandifolia, the American beech, is a common tree in the eastern United States, where it grows from Canada to Florida, and as far west as eastern Wisconsin and Oklahoma and Texas (Fowells, 1965). Beech trees produce large, mammal- and bird-dispersed seeds. The seeds germinate well either on mineral soil or leaf litter. Beech seedlings are slow-growing relative to other hardwood species, but are shade-tolerant and unpalatable to deer (Rushmore, 1961). The persistence of beech in gaps in the Great Smokey Mountains was attributed to the ability of beech to withstand wind (Russell, 1953). In Pennsylvania, beech grew under all physiographic, soil, and site conditions, and was able to reproduce on dry, upper slopes underneath hemlock (Hough and Forbes, 1943).

Beech is also known for its ability to produce root sprouts, a capability which contributes to the persistence of beech at a given site, but not to its spread to adjacent sites (Jones and Raynal, 1986). Root sprouting appears to be more common in northern sites than in sites in the central or southern parts of its geographic range, and more common at higher elevation sites in the southern part of its range (Held, 1983). Both root injury and high density of superficial roots contribute to the occurrence of root sprouts.

Studies near the western range limit of beech in Wisconsin suggest that moister and cooler conditions in northeastern Wisconsin increase seedling production relative to southeastern Wisconsin (Ward, 1961). The author suggested (Ward, 1956) that climatic warming would result in a decline in beech, especially if warming was not accompanied by an increase in moisture. The width of annual rings on beech in Indiana correlates positively with total precipitation and negatively with temperature during June. Ring width was especially sensitive to low summer rainfall (Diller, 1935).

Denton and Barnes (1987), however, found that beech distribution in Michigan was not limited by dry conditions. At this more northern site, beech is found where the ratio of July-August precipitation to potential evapotranspiration is low. They also found evidence that beech was limited by winter temperatures. Thus, beech might be expected to expand northward given a climate warming.

Yellow Birch

The geographic distribution of Betula allegheniensis, yellow birch, parallels hemlock, possibly because of similar requirements for seedling germination (Godman and Mattson, 1980). Yellow birch seeds, like hemlock seeds, are very small, are shed during the late fall and winter, and germinate well on moist, mineral soil (Curtis, 1971; Tubbs, 1969). Establishment of seedlings is irregular and may depend on disturbance, as yellow birch is a shade-intolerant species (Stearns, 1951). Young seedlings can tolerate hot, dry conditions once roots are well established, and growth of yellow birch seedlings increases with increasing light levels (Godman and Krefting, 1960).

There is also some evidence that growth of adult trees is decreased when more than adequate moisture is available. Radial growth of yellow birch on wet sites and on well-drained sites during wet years was reduced over that of drier sites or years, possibly as a result of water-logging in the root system (Fraser, 1956). Seedlings are also reported to be more vigorous and faster growing on well-drained soil.

Sugar Maple

Acer saccharum, sugar maple, is a shade-tolerant, long-lived species with a high reproductive rate. Seeds are produced annually with periodic, large seed crops, are shed in the fall, and buried in the leaf litter (Curtis, 1971). The seeds germinate at lower temperatures than other hardwood species (Godman and Mattson, 1980) so are able to monopolize the resources available in the early spring. Sugar maple seedlings commonly form a dense layer of growth on the forest floor (Stearns, 1951); Curtis, 1971) and then experience high mortality as the cohort ages and resources become limiting.

Sugar maple is a very competitive species because of its ability to survive under densely shaded conditions, to grow fast under high light regimes, and to survive heavy deer browsing.

Climatic Thresholds For Hemlock, Beech, Yellow Birch, and Sugar Maple

Since hemlock seedlings are particularly sensitive to desiccation, warmer and drier climate could eliminate seedling recruitment. Adult trees could also be adversely affected as was seen in Menominee County, Wisconsin, during the drought years of 1930-1937. Menominee County is 50 kilometers northeast of the southwestern edge of the continuous distribution of hemlock. Primary cause of death in a number of adult trees was root death that resulted from a drop in the water table. Both fungal and borer infection were found on dead trees, but infection was a secondary cause of mortality, since only trees with a high proportion of dead roots were infected. Wind storms, the common form of disturbance in the Great Lakes forests, exacerbate the effects of drought, as the removal of the overstory trees alters the microclimate of the understory, leaving seedlings and saplings overexposed to high temperatures and high rates of evaporation (Secrest et al., 1941).

The response of beech to a climate warming is less easy to predict. If beech is limited by cold winter temperatures (Denton and Barnes, 1987), then climatic warming could result in northward expansion of beech's range. Beech's sensitivity to a change in available moisture is less clear. Although Denton and Barnes (1987) found a correlation between the presence of beech in Michigan and low moisture availability, Diller (1935) found that beech growth in Indiana, the western edge of beech's distribution, declines under warmer, drier conditions. Although beech is reported to grow on dry sites in Pennsylvania (Hough and Forbes, 1943), the dry sites in Pennsylvania may have higher available moisture than dry sites in the western Great Lakes region. An increase in temperature in the Great Lakes region would most likely result in moisture becoming limiting for beech, as seems to be the case in Indiana.

Yellow birch's range limits parallel those of hemlock, providing support for the idea that the two species have different thresholds for similar climatic factors. Yellow birch seedling establishment, like that of hemlock, is very sensitive to moisture availability, so an increase in temperature without a corresponding increase in precipitation could result in a contraction from a major portion of the species' present range. Unlike hemlock, however, yellow birch grows as far west as northwestern Minnesota, which has lower annual precipitation.

Sugar maple is likely to fare better than other species in the Great Lakes region after a climate warming. Because of the high number of seedlings produced, and the high amounts of mortality necessary to reduce the population as the cohort ages, there is potential for sugar maple to produce a cohort that is adapted to the conditions at the time of establishment. There is some preliminary evidence to suggest that cohorts differ significantly, but the reason for this can only be inferred (Mulcahy, 1975). Although sugar maple ranges farther west than the other species we have considered and has greater tolerance for lower moisture regimes, it too is limited by moisture and does not grow at the edge of the prairies.

CHAPTER 3

RESULTS OF THE CLIMATE THRESHOLD MODEL

Climatic Variables Used

The climate threshold model is a simple model which compares species' current geographic distributions to temperature and precipitation values to define the species' climate-space. The assumption is made that conditions near a species' range limits represent threshold conditions; within the climate-space defined by these boundaries the species can grow, while outside it cannot.

The output generated by the GFDL and GISS General Circulation Models has been used to forecast a climate-space for each species under $2xCO_2$. Climate alone is considered, not soil fertility, dispersal rates, or any biotic factors.

The climate variables used were mean January temperature, mean July temperature, and annual precipitation. Mean January temperature was used because of the correlation between northern distribution limits for all four species and -15°C mean January temperature. Climate variables are often closely correlated with one another, and there may be one or several variables that are important in determining the threshold for growth for each species. Minimum winter temperature is probably a more meaningful variable for the determination of a species' distribution than mean January temperature, and there is evidence that the killing point for sugar maple, beech, and yellow birch is between 40 and 45°C (Sakai and Weiser, 1973; George et al., 1974). Since output of GISS and GFDL does not include temperature extremes, we have used mean January temperature instead; its coincidence with northern distribution limits suggest it is correlated with temperature extremes.

Mean July temperature was chosen because of its close correlation with the southern distribution of yellow birch and hemlock. Temperature is an important factor in regulating many physiological processes, and has been correlated with initiation of growth in the spring (Fraser, 1956; Larsson, 1979; Hicks and Chabot, 1985), amount of shoot growth in the subsequent year (Kramer and Kozlowski, 1979; Larsson, 1979), changes in competitive dominance (Woodward, 1975), and failure of sexual reproduction (Pigott and Huntley, 1978 and 1981).

Although this is a very simplistic approach to the interaction of climate and vegetation, we feel that it is appropriate for several reasons. Given the scale of the global climate models and the distance between grid points, an analysis more sensitive to climate variation at a specific location would be inappropriate. Second, the output of our model functions best to provide an estimate of potential range distributions for forest species. A more detailed analysis of the distribution, incorporating soil types, competitive interactions, and a finer analysis of climate variables, would be the next appropriate step. Interactions among variables are also important. Higher concentrations of CO_2 will increase the water-use efficiency of plants, possibly reducing sensitivity to drought (Morison and Gifford, 1984).

Climate-Space Under GISS Scenario

The responses of the four species we have considered within the Great Lakes region will depend significantly on the change in precipitation that will accompany a temperature increase. Because the global climate models do not agree on the change in precipitation, we have given a range of possible outcomes. Both scenarios suggest, however, that the ranges of all four of these important forest trees will be reduced substantially within the Great Lakes region.

Given the output of the GISS model, the climate-spaces available for hemlock, beech, yellow birch, and sugar maple are reduced in the Great Lakes region, but the species would not be extirpated from the region

(Figures 1b-4b). The less drastic changes in ranges, relative to the GFDL scenario, are the result of a smaller increase in temperature, accompanied by a slight increase in precipitation. The potential ranges of all of the species contract, as their southern limits move from central or southern United States to the Great Lakes region. Beech, hemlock, and yellow birch would all be reduced in abundance in the Great Lakes region.

Because of the generous spacing between grid points of the GISS model, predicted climate space is largely based on extrapolation between points. Both hemlock and beech in the Great Lakes region would be limited by annual precipitation. Hemlock populations on wetter sites may survive, but the frequency of periods with adequate moisture for seedling establishment would probably decrease. At sites on the western edge of the range, seedling establishment may be so infrequent as to eliminate hemlock from that area, but there will be a time lag between climate change and the decrease of the geographic range because of the longevity of the species. It is to be expected that relict populations will persist in habitats with unusual microclimate.

Beech would decline in the Great Lakes region, limited by annual precipitation. Sugar maple and yellow birch both have a more extensive potential range because of their current distribution on drier sites. Under the GISS scenario, the northern limit of the climate-space for all four species is not determined by winter temperature, but by cool summer temperatures and low annual precipitation in northeastern Canada.

Climate-Space Under GFDL Scenario

Given the GFDL scenario, all four tree species will become extinct in the Great Lakes region (Figures 1c-4c). The predicted increase in summer temperatures in the Great Lakes region -- 7-10 C -- exceeds the climatic tolerances of any of the species under any moisture regime. One would expect not only failure of seedling establishment of the species, but mortality of adult trees also. The predicted climate-space for all of the species (Figures 1c-4c) moves northeastward into Canada; the climate-spaces for sugar maple and yellow birch extend farther west than for hemlock or beech because of their current distribution in drier areas. The western and southern distributions of hemlock and beech are limited by summer temperature and annual precipitation. Within their current distribution, nowhere except Nova Scotia has a climate analogous to climates predicted by the GFDL model.

Rates of Dispersal and Colonization

The paleorecord provides clear evidence that the response of plants to climate change is not instantaneous. Trees grow slowly and take many years to reach maturity. Newly established seedlings of species that may be well-adapted to changed climate may take many years to reach the canopy, owing to shading from the resident canopy dominants (Davis and Botkin, 1985). When large geographic regions are considered, the limited distances of seed dispersal cause lags in the adjustments of species ranges to climate (Davis, 1986; Davis et al., 1986; MacDonald and Ritchie, 1986). In the past, tree species populations have expanded into climatically favorable regions at rates averaging 10-40 km per century (Davis, 1981). In northwestern Canada spruce advanced northward at a record rate of 200 km per century, a dispersal rate that is explained by winds blowing northwestward along the edge of the retreating ice sheet (MacDonald and Ritchie, 1986).

Because climatic changes resulting from doubled CO_2 will occur with unprecedented speed, it is important to consider whether dispersal may limit biotic response. Doubling of CO_2 or the equivalent in radiatively active gases is expected to occur by 2090 A.D. at least. We have therefore considered the possible expansions of species ranges that could occur within 100 years. To display these expansions on maps, we have drawn the predicted species range at $2xCO_2$ to include that part of the present species range that falls within the climate-space projected under a given scenario, plus an extension of 100 km into the unoccupied climate space. This is a generous estimate of the possible range extension that might occur without human intervention, as it is more than double the fastest known range extension for the species in question. (If the extension rate has been doubled to 200 km, the resulting enlargement of range would be insignificant at the scale of the maps shown in Figures 1-4).

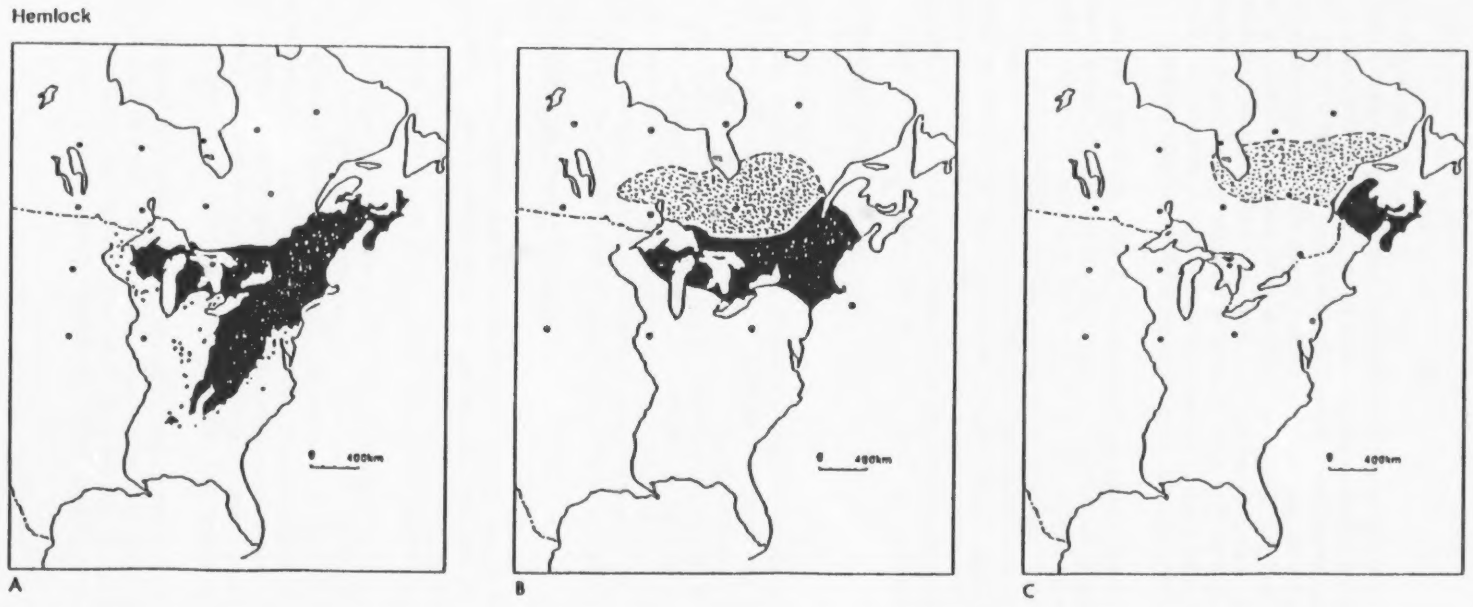

Figure 1. Present and future geographical range for hemlock. A: Present range (modified from Fowells, 1986). B: $2xCO_2$ climate-space in 2090 A.D. under the GISS scenario. Black area is the predicted species range; stippled area is potential range. C: $2xCO_2$ climate-space in 2090 A.D. under the GFDL scenario. Black area is the predicted species range, stippled area is potential range.

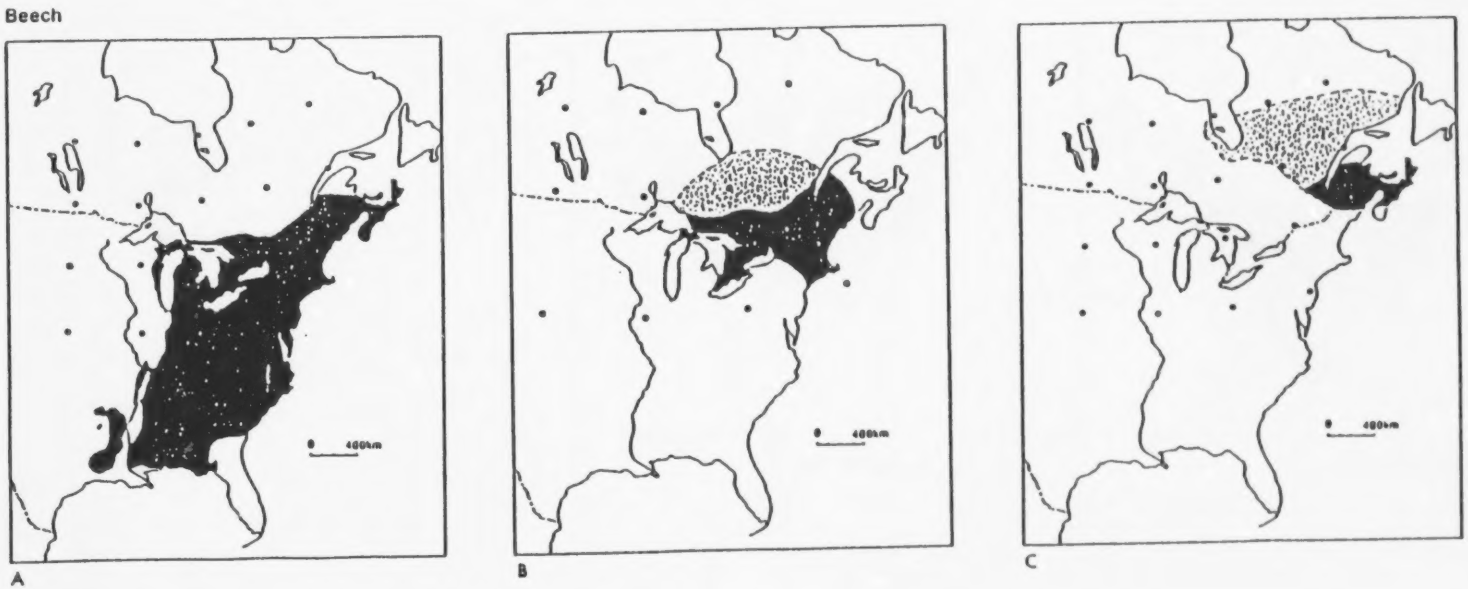

Figure 2. Present and future geographical range for beech. A: Present range (from Fowells, 1965). B: $2xCO_2$ climate-space in 2090 A.D. under the GISS scenario. Black area is the predicted species range; stippled area is potential range. C: $2xCO_2$ climate-space in 2090 A.D. under the GFDL scenario. Black area is the predicted species range, stippled area is potential range.

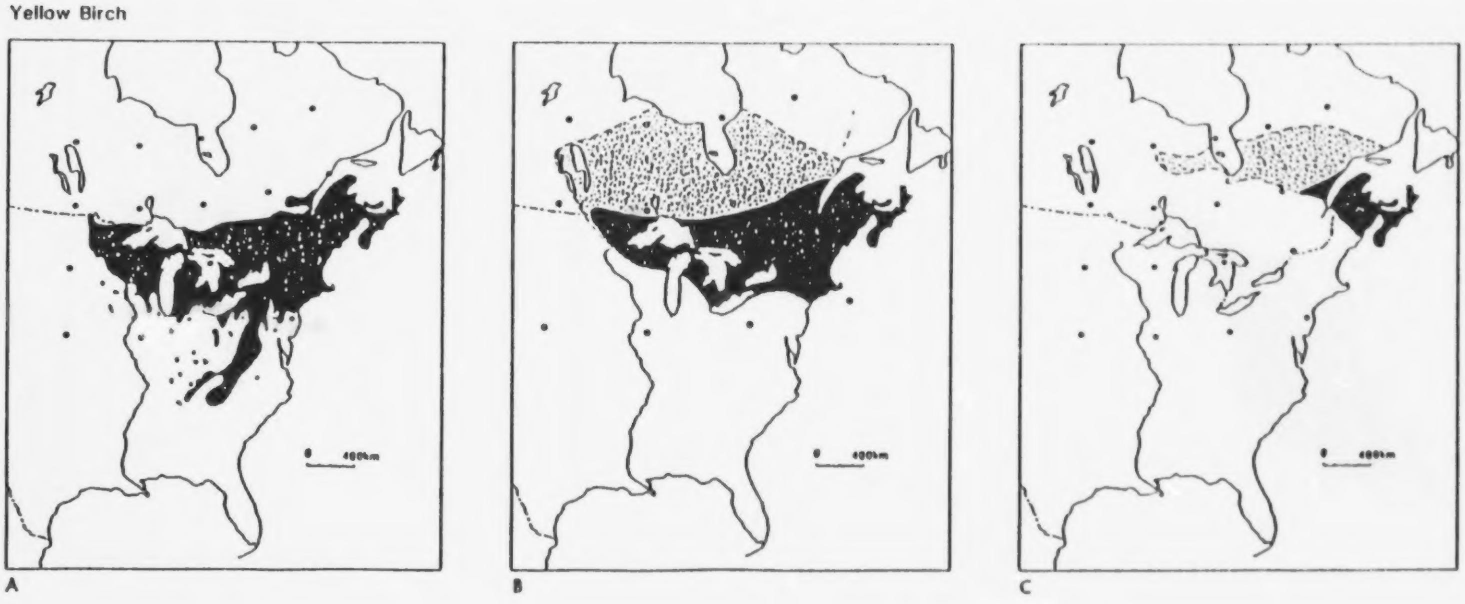

Figure 3. Present and future geographical range for yellow birch. A: Present range (from Fowells, 1965). B: $2xCO_2$ climate-space in 2090 A.D. under the GISS scenario. Black area is the predicted species range; stippled area is potential range. C: $2xCO_2$ climate-space in 2090 A.D. under the GFDL scenario. Black area is the predicted species range, stippled area is potential range.

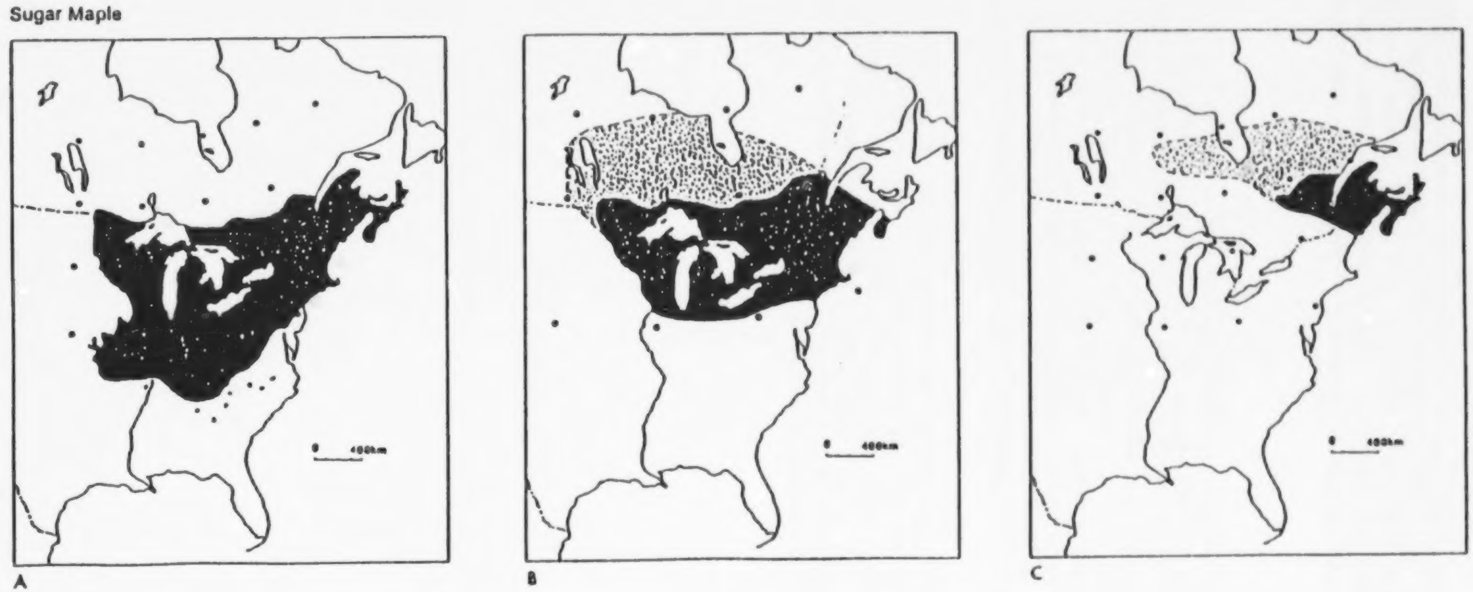

Figure 4. Present and future geographical range for sugar maple. A: Present range (from Fowells, 1965). B: $2xCO_2$ climate-space in 2090 A.D. under the GISS scenario. Black area is the predicted species range; stippled area is potential range. C: $2xCO_2$ climate-space in 2090 A.D. under the GFDL scenario. Black area is the predicted species range, stippled area is potential range.

The differences between the predicted range and the predicted climate-space for each species (Figures 1-4, b and c) is very large in all cases, indicating that dispersal of seeds and establishment of seedlings will be important factors limiting tree distributions in the coming century of rapid climatic change. Means for artificial seed dispersal into climatically suitable regions should be considered. It will be necessary, of course, to develop ecotypes that are appropriate for growth at the high latitudes of the predicted climate-space regions indicated in Figures 1-4, b and c).

Limitations

There is a definite gap in the published literature on whole plant responses to climate and climate change, and on factors determining the range limits of plant species. We need more whole-plant studies along the lines of those by Bordeau (1952) and Woodward and Pigott (1975). Correlating climatic isolines to geographic distributions, and using statistical analysis to determine which factors may limit a species' distribution, are good first steps for generating hypotheses. They in no way compensate, however, for the lack of experiments that demonstrate how whole plants react singly, and in competition with other species, to a change in climate. More needs to be known concerning the direct effects of CO_2 on plants growing in natural ecosystems, and the interactions of direct CO_2 effects and climate on plant response (Bazzaz and Carlson, 1984; Canham and McCavish, 1981; Conroy et al., 1986; Funsch et al., 1970; Higginbotham et al., 1985; Williams et al., 1986; Zangerl and Bazzaz, 1984).

We need to know more about physiological races within species. For example, there is a suggestion that preference by some populations of yellow birch for wet sites in Wisconsin is the result of introgression of yellow birch with bog birch Betula gladulifera (Curtis, 1971). The suggestion of two physiological races of hemlock in Wisconsin, one that grows on dry sites and the other on moist sites, needs to be further investigated. It might be possible, for example, to manage forests for anticipated climate changes by moving ecotypes into areas where they will have some time to become established before a climate change occurs.

CHAPTER 4

IMPLICATIONS

Environmental Implications for the Great Lakes Region

Major reductions in abundances are predicted using the GISS scenario, and loss of four major forest species from the region is predicted given the GFDL scenario. These changes will affect processes of soil formation and will change the productivity of forested lands. Northern hardwood species will be replaced by other trees characteristic of more southern latitudes, or by open prairie or scrubland. Although the species in question will not suffer extinction, ecotypes adapted to continental climates will be lost. Even under the GISS scenario, northern hardwood forest communities will be much reduced in area.

A major loss in biodiversity is to be expected under the GFDL scenario. Extinctions are to be expected among spring ephemerals and other herbaceous species and fungi adapted to the moist, shaded conditions that characterize the forest floor under northern hardwood and beech-maple forests. These plants lack dispersal capabilities sufficient to colonize the predicted hardwood region hundreds of kilometers to the northeast. Under the GISS scenario, many species in the western and southern parts of the Great Lakes region will be endangered because the hardwood forests in these areas will change greatly and contract in area. The marginal climate will stress the trees, resulting in increased mortality from insects and pathogens. Beech will be greatly reduced. The seeds of this species provide food for many birds and small mammal species.

Woodland animals will also be endangered, especially under the GFDL scenario. However, deer populations may be favored by increased early successional vegetation as weakened adult trees are knocked over by wind or die as the result of attacks from insects or pathogens. Successional species such as trembling aspen and paper birch provide fodder, and the deer population can be expected to increase in the same manner it did following logging around the turn of the century. Fires are likely to be more common under the warmer climates predicted by both models, although the heavy rainfall predicted by GISS may cut down the incidence somewhat. Hydrology is unlikely to be greatly affected by the loss of these four tree species alone.

Socioeconomic Implications

Under the GISS scenario, forestry will be hard-hit. Beech will be eliminated from lower Michigan, and yellow birch and hemlock will contract from regions where they grew well prior to CO_2 doubling. Maple will be marginal in the southern Great Lakes region, although it will still grow in northern Wisconsin and Minnesota, and throughout Michigan. Given the GFDL scenario of climate change, the hardwood logging industry of the Great Lakes region will be eliminated completely. Hardwood forests will exist only in Nova Scotia and northern New England, regions with indigenous forestry industries.

At present, most hardwood forests in the Great Lakes region are not intensively managed. In future decades, management will become necessary. Although sugar maple trees will still grow in the region, seeds will probably have to be brought in from the south where varieties are adapted to warm climate. Breeding will be necessary to perfect varieties that withstand heat but have photoperiod sensitivities appropriate for the north. Protection from wildfire, which may occur more frequently with warmer climate, will be necessary for these fire-sensitive species. As the climate changes and trees cease to grow rapidly and begin to show signs of stress, salvage logging operations will be advised. Similar salvage operations will have become necessary some years previously in states to the south; extensive salvage logging may depress market prices for hardwood, make it unlikely that salvaging will be highly profitable in the Great Lakes region.

Methods will have to be developed for broadcasting seeds or seedlings ahead of the northward-moving front for all four species in order to colonize the available climate-space more rapidly than will occur naturally. Given the sensitivity of seedlings of both hemlock and yellow birch, broadcasting seedlings may prove more successful than seeds. Two factors should be investigated before such procedures are widely applied: 1) the suitability of soils in what is now a boreal forest region, and 2) the sensitivity of all four species to photoperiods at the northern latitudes where seeding is to be attempted (Vaartaja, 1959).

CHAPTER 5

POLICY IMPLICATIONS

Policies must be implemented to lessen the economic impact of CO_2 warming on regions where forestry is the main source of livelihood. Salvage logging will provide plentiful short-term jobs, but the long-term outlook for a profitable industry is poor. Research is needed on the kinds of trees that can be grown in the Great Lakes region under changed climate; development of varieties suited to northern latitudes should begin immediately. Methods for introducing economically valuable species into regions where natural seeding is not occurring also need development. To preserve water quality, careful watch should be made on ecosystems where forest dieback is occurring.

The loss of biodiversity has large implications for social and esthetic values. Park managers and the tourism industry have much at stake. Loss of biodiversity will have an economic impact as well. Even for species that are not completely lost, valuable ecotypes will become extinct. Maps showing the response to GFDL-predicted climate demonstrate that all the ecotypes of these four species of trees that are adapted to continental, relatively xeric conditions could be lost from the species' populations. For colonization of the climate-space in the mid-continent, entirely new genetic stock will have to evolve from the relict populations in Nova Scotia and northern New England. Evolutionary changes of this kind are slow within long-lived species; for this reason colonization of the available climate-space might not occur given natural means for thousands of years. In fact, natural dispersal into such a large region would take many centuries, if not several millennia.

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POTENTIAL EFFECTS OF CLIMATE CHANGE ON U.S. FORESTS: CASE STUDIES OF CALIFORNIA AND THE SOUTHEAST

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FINDINGS[1]

The purpose of this review was to assess the potential effects of higher CO_2 concentrations and climate change on forests and their uses in the United States. Three hypothetical scenarios of potential future climate were applied to published information to evaluate how a different climate and higher CO_2 concentrations might affect forest productivity and species composition in California and the Southeast. These trends were compared with socioeconomic trends in these states to assess potential economic effects and public policy issues.

A fundamental question about effects of climate change on forests is what will happen to them when the historic equilibrium climate conditions under which they have evolved greatly change in a very short period of time. Today's tree species in natural forest ecosystems evolved over thousands of years in response to relatively stable climate conditions. Historically, the greatest changes were in response to abnormal weather events, e.g., spring droughts, rather than to long-term averages. The climate change which is projected over the next century will have more abnormal weather events. The ability of species to adapt to the new climate will depend on many factors. Some of the most important are the rate and magnitude of climate change, inherent ability of tree species to grow and compete with other species in a different microclimate, and the degree to which higher ambient CO_2 concentrations can offset negative effects of higher temperatures and droughts.

Some of the tree species and populations most susceptible to climate change are peripheral populations in ecotones near the edges of species ranges, species with limited genetic diversity, specialized species which can only exist within a narrow range of conditions, poor seed dispersers, and some cold-climate species.

Most of the potential effects of climate change will lag many years behind the temperature and precipitation changes presumed in this analysis. Impacts will be difficult to detect, as will ability to ascertain whether they were caused by a real change in climate or natural variability in the present climate. In general, most low-elevation forests in the southern half of the U.S. will probably experience reductions in biomass and species diversity after 100+ years. Higher elevation and more northern forests could become more productive and increase in species diversity.

The risk of tree damage and mortality due to insects, diseases, and wildfires is expected to increase. Warmer temperatures and wetter conditions will generally increase the severity of and potential losses from many insects and diseases. Drier conditions would increase the risk of wildfire losses.

The potential impact of climate change on the policies employed by society to manage and regulate U.S. forests will depend on many factors. The impact will depend in a large part on the economic and noneconomic values that society places on the various commodities and uses of forests and to what extent future climate change impacts those benefits. The dominant factor now determining the uses and benefits are the goals and management policies of the forest owners.

In California, climate change would most likely decrease the productivity and species diversity in many low-elevation forests. Many higher elevation forests could become more productive and increase in species numbers. Higher winter temperatures would reduce mountain snow packs and summer stream flows. Tree mortality will probably increase owing to more wildfires, larger insect populations, and increases in diseases. Foresters will place more emphasis on managing forests for water production, recreation, and reducing losses from forest pests and wildfires. Anticipated decreases in forest productivity will most likely intensify public pressure to legislate more multiple-use practices on private forestlands. A reduced presence of the forest industry is also expected.

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Most southern forests will probably have some decrease in productivity and species diversity over many centuries of climate change. Some upland hardwood forests may become more productive. Climate change will probably favor hardwood forest types more than types containing the commercially important southern pine species. Anticipated trends in reduced softwood production and loss of productive forestland to agriculture will probably accelerate. Forest industries dependent on low-cost softwood will face increasing economic pressures to modernize their manufacturing facilities, increase softwood supplies from their own lands, or move to other regions with more favorable wood supplies and economic conditions. A potentially major loss of forestland to other uses could result in greater regulation of forest practices on private lands.

Public policy implications will vary by region because potential impacts will not be the same across the country. Socioeconomic impacts will depend on forest ownership. Federal forestlands have a legislated policy which can rapidly respond to socioeconomic needs on a regional basis. Private forest owners will be most responsive to impacts on financial benefits. State and local government policymakers are most likely to legislate new policy or regulations concerning forest effects when forest-based tax revenues and socially important values derived from forests need protection.

Some of the most important research needs are 1) more precise regional-scale climate models which can provide more biologically useful information for trees and forests; 2) tree-, forest-, and ecosystem-level models for major species that are sensitive to changes in CO_2 concentrations and microclimate variables; and 3) more information on effects of long-term elevated CO_2 concentrations on seedlings and large trees in forests, especially differences between species.

CHAPTER 1

CLIMATE EFFECTS ON FOREST ECOSYSTEMS

INTRODUCTION

Atmospheric concentrations of carbon dioxide (CO_2) have increased 20% since 1960 and are expected to double pre-industrial levels by the third quarter of the next century. The increase has been attributed to the burning of fossil fuels, worldwide deforestation, and changes in land use (NAS, 1983). CO_2 and other radiatively active or "greenhouse" gases in the troposphere affect the global heat balance of the earth (NAS, 1975b, 1979, 1983; Hansen et al., 1981). Elevated levels of these gases are expected to increase the average temperature of the earth's surface by 1.5° to 4.5°C and alter patterns of precipitation, relative humidity, cloudiness, and related climatic factors in different regions. Although there is no consensus among climatologists that the earth is now warmer because of an increase in "greenhouse gases," there is consensus that the earth should become warmer in the future. There remains considerable uncertainty about when, where, by how much, and how soon climate will change. Assuming that climate does change, there is equal uncertainty about the overall effects of those changes on many aspects of life.

The purpose of this review is to assess the potential effects of higher CO_2 concentrations and climate change on forests and their uses in the United States. In order to detect some of the most likely trends, three hypothetical scenarios of future climate were applied to what is known about climate and CO_2 influences on forest productivity and forestry related socioeconomic trends in California and the Southeast. These results, identified information needs, and some potential public policy concerns are described below.

THE NATURE OF CLIMATE

"Climate" is defined as the sum total of all individual meteorological occurrences, or weather processes, over a period of years in a given place (Geiger, 1965). Climate includes average weather conditions, regular sequences of weather, and repeatedly observed special phenomena such as tornadoes and late frosts.

One of the most important attributes of climate that influences all organisms is the variation of weather conditions over time and space. Light, temperature, and atmospheric moisture conditions are rarely the same for the same dates or months in each year. There are a number of climate anomalies within the context of interannual variability. For example, Figures 1A and 1B show the average March and April temperatures and precipitation values for North Carolina from 1887 to 1982 (Karl et al., 1983). The two horizontal lines labeled 5th percentile and 95th percentile delineate the values that were in the lowest and highest 5th percentiles of values. Although the average temperature for this 96-year period was 12.6°C, actual values deviated from 10.1° to 16.4°. Similarly, annual mean precipitation values varied 100 mm around the long-term mean of 196 mm. Only three of the annual temperatures equaled the long-term average. Only five annual precipitation values were within 5 mm of the long-term average. The years where values are below the 5th or above the 95th percentile lines are considered "extreme events."

The variation in climate factors such as precipitation and temperature is more important to understanding species composition, plant succession, and biomass productivity of plant ecosystems than long-term averages. Ecosystems exist in a state of "dynamic equilibrium" with their climates, and plants are constantly striving to respond to changes in temperature, precipitation, etc. They often respond to normal annual cycles of these values in a fairly predictable manner until extreme events, e.g., unusual droughts or frosts in the spring, cause unexpected departures from the normal equilibrium condition. One of the most critical questions about future global climate change concerns how these dynamic aspects will change. Will the frequency of abnormal events that injure, weaken, or kill plants increase or decrease from the historical climate?

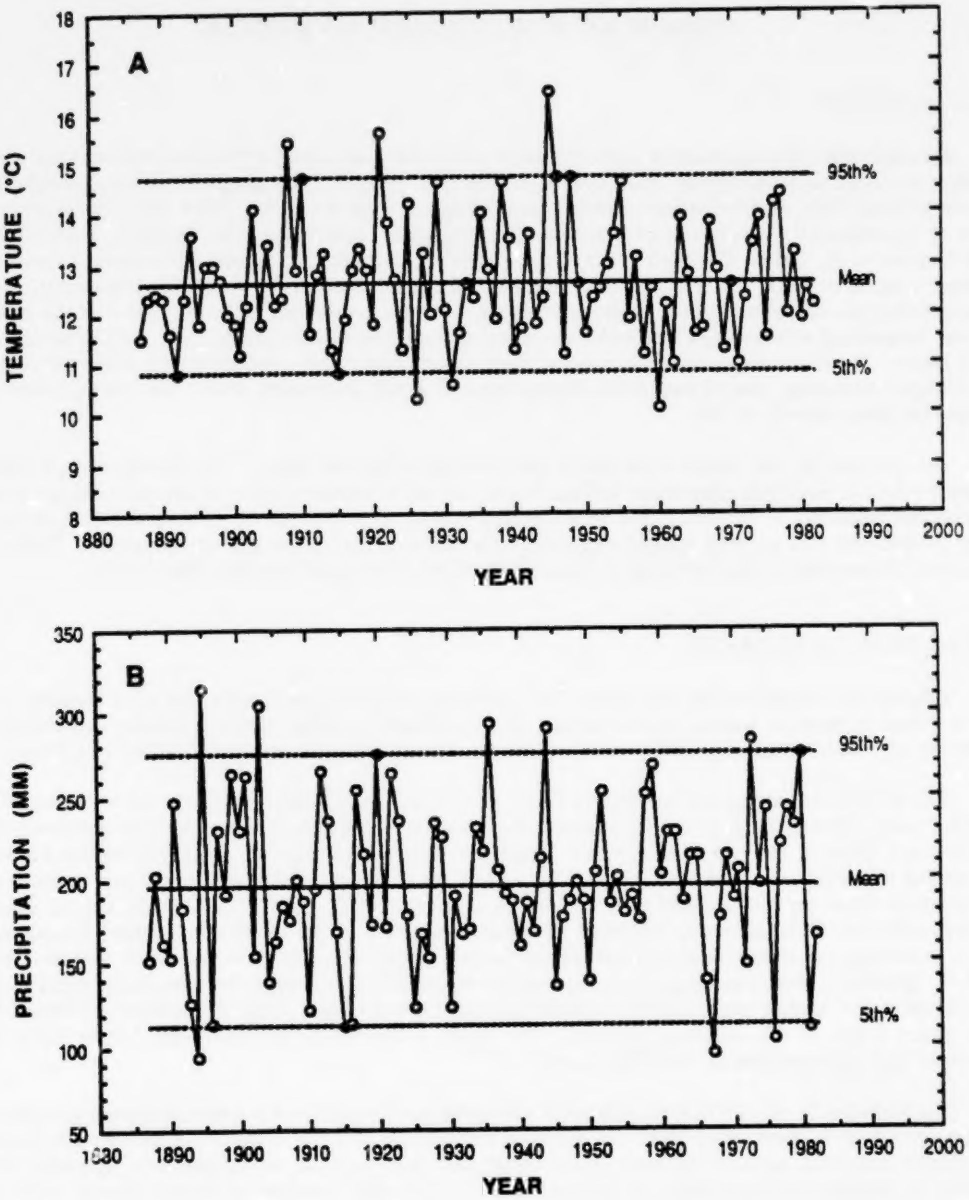

Figure 1. Average temperature (A) and precipitation (B) for North Carolina for March and April from 1887 to 1982 (Karl et al., 1983).

The factors of climate that affect plants are usually different from those depicted in historical climate data (Geiger, 1965). Most weather data used in climate averages are taken from stations located outside the influences of plants. Data from all stations in a region are averaged to characterize that region's "macroclimate." The meteorological conditions within 2 meters of the ground or within a plant canopy are called microclimate or plant climate (Geiger, 1965). Plants create their microclimate by altering solar energy flux, wind movement, and precipitation reaching the soil surface. They modify air and soil temperatures by increasing humidity through transpiration, shading, and lowering wind speeds. Summer temperatures are often 2° to 3° cooler and relative humidities 20% to 30% higher within forests than in the surrounding macroclimate.

Because forests do modify their environments, there may not be a strong correlation between annual or short-term weather events and the response of plants or ecosystems to these events (Geiger, 1965). The degree of correlation will depend on each ecosystem, the type and duration of abnormal climate events, and the presence of other stress-inducing factors in the ecosystem. Thus, future climate change estimates of mean monthly temperatures, precipitation rates, etc., have limited value in assessing trends and impacts on terrestrial ecosystems.

ESTIMATING CLIMATE CHANGE

One method of forecasting future climate changes is to simulate known and theoretical effects of higher greenhouse gases in the earth's atmosphere using general circulation models (GCMs) that have been developed by atmospheric scientists (Hansen et al., 1981; Rind, 1987). GCMs simulate average climate conditions on the earth's surface using specified levels of CO_2 and other greenhouse gases. All existing GCMs project higher average surface temperatures with a doubling of atmospheric CO_2 over pre-industrial levels of 300 parts per million (ppm). These projections differ in the relative amount of temperature increase and direction and magnitude of precipitation change.

GCMs have several deficiencies which limit their present usefulness in assessing effects of climate change on forest ecosystems. The most serious is lack of adequate spatial resolution. They can only project mean values for very large areas encompassing thousands of hectares. They cannot make projections for areas as small as states or regions within states. They cannot predict interannual variation of micro- or macroclimate variables or the probable frequency of extreme weather events. They assume that climate change will not alter spatial and temporal variation.

Given these limitations, three hypothetical scenarios of climate change were developed to derive some indication of how they might affect forest productivity and species diversity in California and the Southeast. These scenarios were developed by applying ratios of climate change from three GCM models to historical data from the National Climate Center for the period 1931 to 1980 (Gibbs and Hoffman, 1987). The GCMs were developed by the Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), and Oregon State University (OSU). All GCMs assumed a doubling of CO_2 concentrations. Sample values from each scenario are shown with the descriptions of each region. These are only hypothetical scenarios of climate change and are not predictions of change.

EFFECTS OF HIGHER CO_2 AND CLIMATE CHANGE ON FORESTS

Today's natural forest ecosystems and tree species have evolved in response to long-term climate conditions. The species diversity in these ecosystems is the product of a relatively slow process of natural selection which took place over thousands of years. Thus, the fundamental biological question about future climate change centers on how forests will respond to unprecedentedly large and rapid increases in temperature and ambient CO_2, and changes in precipitation. How will North American forest types respond to an increased number of extreme hot days or major increases or decreases in precipitation? How long will it take for them to adjust to a new stable climate? How will the productivity and species diversity of these forests be affected as they adjust to a new climate?

The problem of predicting effects of climate change on the health and productivity of American forests is similar to the problem of detecting and quantifying impacts of air pollution on forests (Woodman and Cowling, 1987). Trees and forests have the inherent ability to tolerate or adapt to many stresses such as competition, resource deficiency, herbivory, and environmental extremes (Chapin et al., 1987). Tree death is often the result of a combination of factors (Franklin et al., 1987). We lack baseline information on "normal" patterns of forest development, succession, and mortality. Without it, it will not be possible to separate and quantify the direct effects of climate change on forest productivity or health.

Paleobotanical studies provide insight into changes in forest composition and rate of change of past climate conditions. Using pollen data, Bernabo and Webb (1977) concluded that over a temperature increase of 4° to 8°C, four major North American forest types migrated at the rate of about 100 km per 1,000 years over the last 11,000 years. These forest regions stabilized in their present form about 6,000 years ago but have undergone small changes since then because of slower migrating species. Gajewski (1988) described variation in the composition of eastern North America vegetation on time scales of centuries or millennia. Bernabo (1981) was able to detect species changes on time scales of decades to centuries.

Physical Climate Effects

High temperatures generally increase the rate of transpiration and the potential for dehydration in plants. Because the temperature optimum of respiration is higher than that of photosynthesis, carbohydrates may be depleted (Kramer, 1980). Very high or prolonged leaf temperatures can induce denaturation of proteins and membrane damage, causing cell injury (Levitt, 1980). Nonlethal heat injury ("sun scald") in mature trees can occur on the south sides of thin-barked species. Heat injury is more common on recently germinated or planted seedlings on sites when the soil is exposed to direct insolation. Bark near the soil surface is killed by acute temperatures, often resulting in seedling death (Levitt, 1980).

Water stress is the factor most often limiting tree growth (Kramer and Sionit, 1987). Combinations of temperature, low precipitation, and low humidities create internal stresses that reduce transpiration and uptake of nutrients because of complete or partial stomatal closure. Sustained drought conditions reduce photosynthesis rates and cause premature foliage loss, which result in depletion of carbohydrate reserves and reduced growth potential (Waring, 1987; Schulze et al., 1987). The cumulative effect of many transitory temperature and water stresses over a growing season is reduction of tree growth (Levitt et al., 1980). The formation of low density "earlywood" and high density "latewood" in conifers is influenced by changes in seasonal temperature and precipitation (Miller et al., 1987).

Carbon Dioxide Effects

Considerable research has been done to elucidate the effects of increased CO_2 concentrations on plants (Rose, Volume C). However, most of it has provided information on short-term responses of herbaceous species (Pearcy and Bjorkman, 1983). Research on woody plants has also been generally short-term and conducted on seedlings in controlled chambers rather than on large trees in forests. Although seedling studies have provided insight into the physiological mechanisms through which microclimatic factors control individual plant growth, there are no mature tree or general forest process models which link effects within a tree to effects at the forest level. Experimentation at the ecosystem level has been limited primarily to arctic tussock tundra (Oechel and Strain, 1985). Predictions of effects on forest ecosystems are mostly based on the tundra research and extrapolations from seedling studies.

Sionit and Kramer (1986) and Kramer and Sionit (1987) have summarized research findings on the direct effects of increased CO_2 on tree physiology and growth. Higher CO_2 concentrations increase the height, stem diameter, and dry weight of most seedlings through increases in photosynthesis rates, inhibition of photorespiration, decreases in stomatal conductance of CO_2 and water vapor, and increases in foliage area. The optimum temperature for photosynthesis may increase at elevated CO_2 levels. Other effects of higher CO_2 include increased branching, leaf area, and leaf thickness. Flowering and seed production is increased in some tree species.

Climate-Carbon Dioxide Climate Interactions

Fried et al. (1986), Houpis et al. (1986), and Surano et al. (1986) studied effects of two years of high CO_2 (600+ ppm) concentrations on ponderosa pine seedlings and saplings in a normal forest microclimate. Their research suggested that higher CO_2 could have detrimental effects on some trees. They found that trees in an ambient plus 300 ppm CO_2 environment had greater stem growth than untreated trees in the first year but grew substantially less in the second. The trees in the higher concentration had reduced total foliage area owing to injury that killed half of each needle. Surano et al. (1986) speculated that this injury was caused by acute foliar heat stress resulting from reduced transpiration rates. Surviving needles had less chlorophyll and carotenoid concentrations (Houpis et al., in press). The net effect was that trees in ambient CO_2 grew more biomass after 2 years than the trees in the high CO_2 environment.

There is some experimental evidence that higher CO_2 could change the competitive abilities of various species in the same microclimates (Sionit et al., 1984; Tolley and Strain, 1984, 1985). Tolley and Strain (1984, 1985) found that the amount of CO_2 fixed by photosynthesis per unit of water (water-use efficiency) in high CO_2 environments was greater in seedlings of sweetgum (Liquidamber styraciflua L.) than in loblolly pine (Pinus taeda L.). In most cases, higher CO_2 partially compensated for effects of water stress on tree growth. It is unclear to what extent elevated CO_2 can completely overcome negative effects of moisture stress and if there are differential effects on other species. If increased CO_2 is in general less favorable for gymnosperms (conifers) than angiosperms (hardwoods), this could have significant implications on future species composition of natural forests.

Higher CO_2 levels may also compensate for the negative effects of higher temperatures on photosynthesis rates. Leverenz and Lev (1987) speculated that doubled CO_2 might raise the optimum temperatures for photosynthesis by as much as 10°C. They also suggested that a doubling of CO_2 could offset growth losses resulting from up to a 5°C increase in temperatures. It is not known if higher CO_2 would affect the chilling requirements of some species (Leverenz and Lev, 1987).

Ecosystem Effects

Peters and Darling (1985) identified the following types of species and communities which would be most vulnerable to climate change: 1) peripheral populations in ecotones near the edges of species ranges; 2) geographically localized species which have no populations in other areas of suitable habitat; 3) species which do not have the genetic diversity to adapt to a different climate; 4) specialized species which require a narrow range of environmental conditions during some phase of their life; 5) poor seed dispersers; 6) montane and alpine species which would have no place to migrate and avoid competition with other species; 7) arctic communities, if temperature increases are higher toward the poles; and 8) coastal and freshwater lowland communities, which will be subjected to more flooding, higher water tables, and saltwater damage.

No direct experimental evidence is available to predict the individual and interactive effects of CO_2 and CO_2-induced climate change on forest ecosystems. Extrapolation from experimentation on individual plants is limited mainly by lack of information on physiological processes that would allow scaling up of data from exposures of minutes or hours to monthly or yearly estimations, and lack of micrometeorological data concerning interactions of vegetation with the atmosphere (Shugart et al., 1986). Differential species responses within an ecosystem to altered climate would logically lead to changes in structure and function, but predictions are not feasible with presently available data (Dahlman et al., 1985).

The effect of climate change will depend on the phase of forest development at the time of climate-induced stresses. They are 1) establishment phase, 2) self-thinning phase, 3) transition phase, and 4) steady-state phase (Peet and Christensen, 1987).

The establishment phase is characterized by establishment of tree seedlings and rapid increases in mass of young vegetation (Peet and Christensen, 1987). This usually follows after a disturbance, e.g., timber harvesting,

harvesting, wildfire, abandonment of cropland. It may last from one year to many years depending on the availability of seed sources, severity of microclimate conditions, condition of soil surface, presence of competing plants, predation by animals and insects, and other factors. Soil moisture, light, and temperature conditions during the first 60 to 90 days after seed germination are very important to seedling survival and growth. Most seedling mortality is related to environmental factors. Conifer seedlings are especially vulnerable to high temperatures at the soil surface (Levitt, 1980). Hardwood species have a competitive advantage over conifers in some situations because most regenerate from sprouts which are more tolerant of extremes in microclimate. The microclimate in newly regenerated forests can be more severe than the surrounding macroclimate until the plants become dense or large enough to modify it.

The self-thinning phase begins when the forest canopy closes and competition between plants for resources becomes most intense (Peet and Christensen, 1987). As some trees increase in size more rapidly than others, the slower-growing and less vigorous individuals cannot obtain enough light, moisture, and other resources to survive (Waring, 1987). Smaller and less competitive trees are susceptible to any perturbations which exacerbate their struggle for limited resources or give competitive advantage to other individuals. Climate-induced stresses, especially droughts, reduce growth rates (Fritts, 1976; Cook et al., 1987) and increase tree mortality. Competitive stresses predispose weaker trees to attacks from insects and diseases (Boyce, 1948; Manion, 1981).

Tree mortality in the transition phase is more often a result of insects, disease, lightning, and windthrow than of competition (Peet and Christensen, 1987). Death of a dominant or codominant canopy tree forms a gap which cannot be completely filled by lateral growth of adjacent trees. Consequently, new seedlings become established, and previously established seedlings and suppressed trees receive enough light and other nutrients to increase in size. Forest trees in this stage of development are generally less sensitive to most climate stresses except droughts.

The steady-state phase is dominated by climax species of varying ages distributed as relatively even-aged patches within previous canopy gaps (Peet and Christensen, 1987). The forest exists as a mosaic of various tree sizes and ages, sometimes overlapping and sometimes distinct. In reality, large-scale episodic perturbations such as insect outbreaks and windthrow occur often enough that most stands do not appear to reach steady-state. Drought-related stresses, wildfires, wind storms, etc., are the most common causes of the relatively low tree mortality rate characteristic of this type of forest.

Forest management practices of artificial thinning and fertilization can compensate for some of the negative effects of higher temperatures and drier conditions (Smith, 1986). In severe and highly variable climates, artificial regeneration methods reduce the risk of excessive tree mortality (Daniel et al., 1979; Tappeiner et al., 1986). Site preparation, weed control, and nutrient additions are also used to increase tree survival and growth during establishment. Some of these methods are used to establish and maintain many tree species, e.g., loblolly pine, outside their natural ranges.

Forest Productivity and Species Composition

Shugart et al. (1986) summarized results of climate change on forest succession using "gap-phase" forest simulation models. They concluded that intermediate and long-term changes in the extent, location, and composition of forests could take place over hundreds of years. High-latitude and boreal forests would be very sensitive to increased temperatures. Tropical and sub-tropical forests would be more responsive to precipitation changes than to temperature increases.

A recent study on the potential effects of a GISS-based climate change scenario on a forest type in eastern Tennessee indicated that these climate conditions would have to exist for hundreds of years before permanent change in species composition and structure would occur (Urban and Shugart, this volume). Shorter-term changes (over decades) would be very difficult to distinguish from the natural variability in forest dynamics.

OTHER EFFECTS ON FORESTS

Insects and Diseases

Hedden (1987) summarized the possible effects of elevated CO_2 and associated climatic changes on forest insect pests. There are no direct effects of CO_2 on insect pests, but temperature and moisture changes will alter the growth and survival of some species. Higher temperatures could increase the number of some insect generations each year. Changes in moisture may also affect the kind, abundance, and behavior of many insect species. Because insects have much higher reproductive rates than trees, they will most likely respond more quickly to climatic change than forests.

Tree-pest interactions will also be influenced by changes in the susceptibility of trees to attacks. Trees in suboptimal sites would be most vulnerable to increased attacks (Miller et al., 1987). Future hardwoods are expected to have greater carbon-to-nitrogen contents in their leaves which would require defoliating insects to consume more foliage to satisfy their nitrogen requirements (Hedden, 1987).

According to Hepting (1963), various combinations of climate factors act as constraints against outbreaks of severe forest diseases. If any of these normally restraining conditions are altered, major epidemics could result. Relatively small increases in temperature could increase the severity of a disease depending on its optimum temperature. He postulated that temperature increases would increase the northern range of many pathogens and cause some tropical diseases to move into North America.

Wildfires

Future temperature increases and decreases in precipitation could greatly increase wildfire activity in most forest regions. Historically, wildland fire activity is related to the relative flammability of "fuel groups" (plant species, vegetation type, size of material) and regional weather patterns (Simard and Main, 1987). The most important weather factors affecting the incidence and severity of fires are temperature, barometric pressure, wind velocity, and the moisture content of fuel groups (Pyne, 1984). The USDA Forest Service integrates weather conditions such as 24-hour mean air temperature, relative humidity, and precipitation with fuel moisture estimates to project fire behavior (Deeming et al., 1977). Higher temperatures and lower precipitation reduce fuel moisture and increase the chances for a fire to start and spread rapidly through a forest. Botkin et al. (this volume) suggested that climate change-induced increases in tree mortality and loss of vigor may also increase the probability for more wildfires.

SUMMARY AND CONCLUSIONS

The tree species that exist in natural forest ecosystems have evolved in response to long-term climate conditions that have inherent associated variability. The potential climate change induced by increased concentrations of "greenhouse gases" will increase the frequency of abnormal events as well as mean climate values. Forests have historically responded more to interannual variation and extreme events than to long-term averages in climate values. A fundamental question is what will happen to forests as the historic equilibrium climate conditions to which they have evolved change. The answer is complex, and will depend in part on the amount and direction of change and the inherent ability of the tree species to adapt to the new conditions. Tree species that have large genetic diversity will show the greatest resiliency to climate change. Species with narrow diversity are most likely to be adversely impacted.

Effects of climate change on U.S. forests will undoubtedly lag behind projected increases in temperature and changes in precipitation. Impacts will be difficult to diagnose as an effect of climate change and not natural variation in extreme weather events. Long-term consequences will depend on the nature of climate change, effects of higher CO_2 concentrations on plant processes, sensitivities of species to changes, forest development stages, soil fertility, changes in insect and disease populations, and many other factors. In general, most low-elevation forests in the southern half of the country will probably experience reductions in biomass productivity and species diversity after 100+ years. Forests at higher elevations and more northern latitudes could become more productive and increase in diversity.

Climate change will increase the risk of tree damage and mortality due to insects, diseases, and wildfires. Warmer temperatures will favor more cycles of most bark beetles and harmful insects. Warm temperatures and moister conditions would favor the spread and severity of many pathogens. These trends with higher climate-induced stresses could cause major losses in unmanaged, older, and more dense forests.

Some of the most important research needs are 1) more precise regional-scale climate models which can provide more relevant information for trees and forests; 2) tree-, forest-, and ecosystem-level models for major species which are sensitive to inputs of higher CO_2 concentrations and changes in microclimate; and 3) more information on effects of long-term elevated CO_2 concentrations on seedlings and large trees in forests, especially differential species effects.

CHAPTER 2

FOREST-RELATED SOCIOECONOMIC SYSTEMS AND POLICIES

The potential impact of climate change on the policies employed by society to manage and regulate the forests of the United States will depend on many factors besides the direct and indirect effects on plants, animals, other organisms, and abiotic systems which are part of forest ecosystems. It will depend in a large part on the economic and noneconomic values which society places on the various commodities and uses of forests and to what extent future climate change impacts those benefits. Estimates of the effects of climate change on the socioeconomic values of forests are even more difficult to make than estimates of impacts on trees and forest ecosystems. Such estimates require projections of future socioeconomic values of forests with and without climate change. They necessitate estimations of future management objectives of forest owners and trends in regional and state forest policies and regulations. One must also consider trends in population growth, urbanization, regional land use, resource-based economies, employment opportunities, economic standards of living, development of new technologies, environmental protection, and other factors.

INSTITUTIONS AND POLICIES AFFECTING FOREST USE AND MANAGEMENT

The dominant factor now determining the uses and benefits derived from United States forests are the goals and management policies of the forest owners. These management policies are influenced by productivity of the land for timber and other forest-derived goods and values, the goals or reasons for ownership, and constraints against achieving these goals. Some of the most common constraints for intensive management on privately owned forestland include unprofitable timber prices, lack of capital for investment or development, and forest practice regulations in some states. National, state, and local political and economic conditions determine options for management of public forests. Thus, the potential impact of climate change in a given area will greatly depend upon regional forest ownership patterns and the regional opportunities for forest owners to achieve their goals.

Non-Industrial Private Forestland (NIPF)

Most of the 194.9 million hectares (ha) of commercial timberland in the United States is owned by private individuals (Figure 2). The USDA Forest Service defines "commercial timberland" as land on which 10% of the area is now or was formerly occupied by forest trees capable of producing 1.4 m^3/ha (20 ft^3/ac) of industrial roundwood per year (USDA, 1982). In 1977, 72% (140.3 million ha) of the nation's commercial timberland was owned by about 7.8 million private individuals and nonforest industry companies, mostly in parcels less than 200 ha in size (USDA, 1982; Birch, 1983). Farmers, who are the single largest group of owners in this class, own 33.4% (46.8 million ha) of the total private forestland.

Binkley (1983) estimated the economic value of timber from non-industrial private forestland (NIPF) to be $600 billion in 1982. Besides the production of income from sales of timber, reasons for ownership of private forestland include esthetics, recreation, land investment, and inclusion in farm or residential property. Due in part to the wide diversity of interests of owners, less than half of NIPF land is deliberately managed in some way for timber, wildlife, recreation, or other uses. Decisions to plant trees and actively manage for timber production are often determined by current government-funded incentive programs, the availability of free or low-cost management advice, and state and regional regulations.

Forest Industry-Owned Forestland

The forest industry owns or controls 14.3% (27.8 million ha) of the commercial timberland in the United States (Figure 2). Although a few companies own forests only for the purpose of growing and selling wood to others, most forest industry companies that own forestland use their wood in their own facilities. In almost all

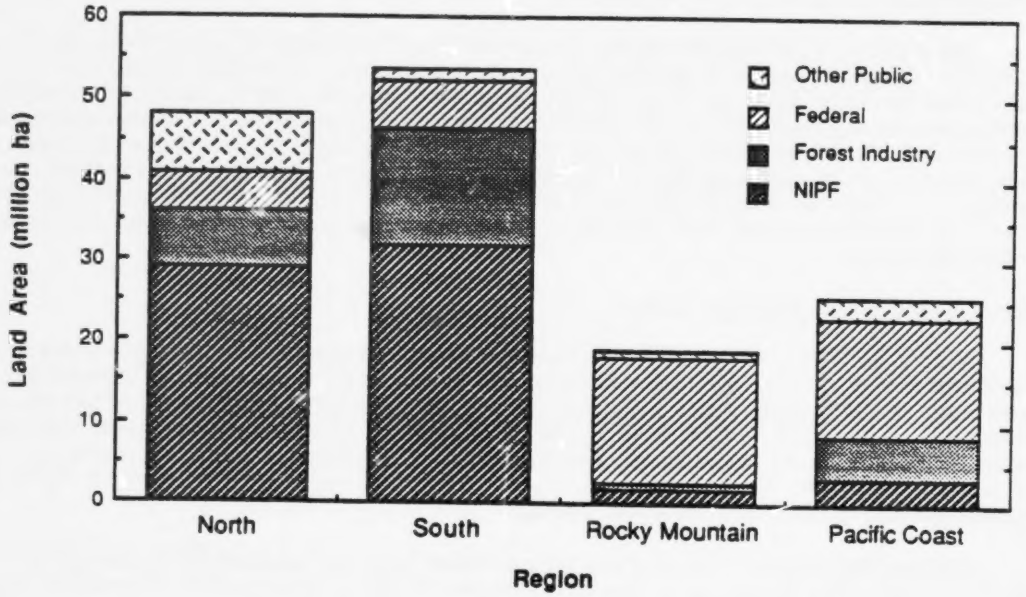

Figure 2. Area of commercial timberland by region and ownership (USDA, 1982).

cases, their primary reason for owning forestland is to maximize profits from it. This is usually accomplished by producing low-cost wood for manufacturing facilities and ensuring that a long-term wood supply is available for their mills.

The relative intensity of industrial forest management, as measured by dollars invested in regeneration and silvicultural activities, is also influenced by the availability of cheaper timber from NIPF and public forestlands. The current surplus of such wood in the Northeast and Lake States is a major factor in the low level of management now practiced in these regions (Benzie et al., 1986; Rose et al., 1987). Likewise, the large supply of low-cost timber available from national forests in the Northern Rockies and Pacific Coast states has reduced management incentives on industrial land in these states (Tappeiner et al., 1986).

In all regions, most forest products companies depend on wood harvested from NIPF and public forestlands. Only a few companies can satisfy all of their wood requirements from timber grown only on their own lands. Thus, the potential impact of reduced forest productivity from climate change will vary by company and by region. The greatest impacts will occur where current timber supplies now balance demand or where shortages in certain types of wood are predicted by the year 2030. Using a GFDL climate model-based scenario, Rose et al. (1987) projected a 30% shortage of softwoods and a surplus of hardwoods in the Lake States and North Central regions. Some shortages in hardwoods and softwoods have been projected in a few small areas of the South, irrespective of climate change (Healy, 1985; Rose et al., 1987).

Public Forestland

Altogether, federal, state, and local governments own or control 27% (54.7 million ha) of commercial forestland (USDA, 1982). Federal forestlands are managed for various purposes by the U.S. Department of Agriculture (USDA) Forest Service (39.9 million ha), U.S. Department of the Interior (USDI) Bureau of Land Management (BLM) (2.3 million ha), USDI National Park Service (NPS), and U.S. Department of Defense.

The management goals for national forests are regulated by a complex set of legal directives and administrative procedures. The most important are the Organic Act of 1897, the Multiple Use-Sustained Yield Act of 1960, the Wilderness Act of 1964, and the National Environmental Policy Act of 1970. The Forest and Rangeland Renewable Resources Planning Act and the National Forest Management Act, passed in the mid-1970s, require that 15-year management plans for each national forest incorporate the public needs and uses of the forests for the region in which they are located.

The Federal Land Policy and Management Act of 1976 gave the USDI BLM statutory responsibility to manage their lands under principles of multiple use and sustained yield. It also prescribed that decisions be based on inventory and land-use planning involving broad public participation.

The USDI NPS is responsible for managing all national parks, monuments, historic sites, national recreation areas, and national wild and scenic rivers. Its legislated goal is to protect each park's natural and scenic attributes for the "unimpaired enjoyment of future generations and to manage them for the use and recreational benefits of the current generation." This is accomplished through a comprehensive long-range planning process and system of management zoning. Some of the controversial management strategies utilized on these lands include permitting wildfires to run uncontrolled in parks, eliminating exotic plants, and controlling human access to sensitive wilderness areas.

POTENTIAL EFFECTS OF CLIMATE CHANGE ON FOREST USE AND MANAGEMENT

No assessment of the effects of climate change on non-industrial private forest owners or public forest managers has been published to our knowledge. Many NIPF owners do not have the financial resources, flexibility, or incentives to dramatically alter their current management practices. Increased risk associated with the stress of climate change may prove an added detriment to long-term investments in intensive forest management by these owners. Because forests which are unmanaged are likely to be at greatest risk from projected climate changes, this class of forest ownership will most likely show the greatest negative effect in the future. The forest industry's reliance on NIPF wood in some areas will cause reverberations in that sector as well. The future productivity of private forests may be forced to rely on more extensive use of intensive forest management techniques. In order for this to come about, greater incentive measures may be necessary, or even increased regulation of forest practices.

The current statutes and management policies of the USDA Forest Service and USDI BLM are sensitive and flexible enough to respond to climate change given all its present uncertainties. Mandated preparation of management plans based on environmental, biological, and economic information should give federal managers a good framework for responding to climate changes. The public is likely to have greater need in the future for the products, both economic and unpriced, that are derived from state and local forests, and the ability of the forests to provide them will depend upon rigorous long-term planning and strict management policies.

Given the large uncertainty about climate change on the biology and economic values in major U.S. forest regions, the forest industry will probably take a "wait-and-see" attitude about global climate change before altering their management strategies. Most companies do not make major decisions based on long-term plans for periods greater than 5 to 10 years in the future. The response of the forest industry to climate change will depend on how quickly changes occur and can be measured. Malac (1987) suggested that adaptation of specific management practices or defensive actions will always lag behind climate change because of the high degree of uncertainty of the changes on a particular region.

Sandenburgh et al. (1987) suggested that forest products companies could minimize the negative impacts of climate change by acquiring forestland in areas with little or no predicted impacts on forest productivity, placement of new manufacturing facilities in lowest impact regions, and choosing future markets where climate change may increase profits. Larger companies could move their manufacturing plants and forestland operations to regions where they can make the highest profit. Since profitability, rather than productivity, primarily motivates industry decisions, climate change could reduce forest productivity but increase profits if higher prices are paid for wood products. Likewise, negative impacts on other forest regions in the world could improve profitability through increased exports of wood products to other countries.

CHAPTER 3

POTENTIAL CLIMATE CHANGE EFFECTS ON CALIFORNIA FORESTS

INTRODUCTION

California is the second largest state in the continental United States. Its 33.6 million ha of forests and rangelands produce a variety of goods and services of importance to the inhabitants of the state, the nation, and the world. Nearly all annual water runoff in the state falls as precipitation on forested watersheds. In addition, forestlands provide habitat to more than 650 different wildlife species, provide 15% of the average annual U.S. production of softwood, support the grazing of nearly 2 million head of range livestock, and offer recreational opportunities for millions of visitors each year (CDF, 1988).

Geography and Climate

California has some of the most diverse and striking landscape and physical diversity in the country (Britannica, 1982). Its long and relatively mountainous coastline ranges in elevation from 610 to 2500 m, while the eastern portions of the state are occupied by relatively flat, sparsely settled desert. The Sierra Nevada Mountains, in the eastern central region of the state, contain 11 peaks which exceed 4250 m in altitude. The Central Valley, a 140-km trough between the Coast Ranges to the west and the Sierra Nevada to the east, constitutes the state's agricultural heartland (Dudek, Volume C). Most of the densely populated area known as southern California is located on a coastal plateau and in valleys within 65 to 100 km of the coast, separated by the Transverse Mountains from the Central Valley.

California has a Mediterranean-type climate characterized by hot, dry summers and frequent summer droughts. Great temperature contrasts exist across the state because of the influences of mountains, deserts, and the ocean. Summer temperatures in the southeastern desert often reach 54°C. Maximum daily temperatures in the high-elevation eastern desert (1220 to 2300 m) range from 24° to 32°C. Although most of the annual precipitation occurs in the fall and winter months, mean monthly precipitation varies similarly to the example for North Carolina (Figure 1B). Annual rainfall ranges from the extreme annual mean of 4420 mm in the northwest to traces in the southeastern desert.

FOREST RESOURCES

Major Forest Types

The natural vegetation of the state has been grouped into five broad cover types: conifer, hardwood, shrublands, grasslands, and desert (CDF, 1988). Only a small portion of the hardwood cover class meets the definition of commercial forest. Approximately 21% of the commercial forests are of the conifer cover type. The seven most commercially important vegetation types, as defined by the California Division of Forestry (1988), within the conifer type are as follows:

- Mixed Conifer (40%) - mainly ponderosa pine (Pinus ponderosa Laws.), Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco), white fir (Abies concolor (Gord. & Glend.) Lindl. (ex Hildebr.)), incense-cedar (Libocedrus decurrens Torr.), sugar pine (P. lambertiana Dougl.), and Jeffrey pine (P. jeffreyi Grev. & Balf.). California black oak (Quercus kelloggii Newb) is a major hardwood associate;
- Ponderosa Pine (11%) - mostly ponderosa pine. Associated species may include white fir, incense-cedar, Coulter pine (Pinus coulteri D. Don), Jeffrey pine, sugar pine, and Douglas-fir;

- Red Fir (8%) - mostly red fir (Abies magnifica A. Murr.) with some lodgepole pine (Pinus contorta Dougl.) and noble fir (Abies procera Rehd.);
- Douglas-Fir (8%) - mainly Douglas-fir, but may include sugar pine, ponderosa pine, Jeffrey pine, incense cedar, redwood (Sequoia sempervirens (D. Don.) Endl.), tanoak, madrone (Arbutus menziesii Pursh), and canyon live oak (Quercus agrifolia Nee);
- Redwood (7%) - redwood with Douglas-fir, sitka spruce (Picea sitchensis (Bong.) Carr.), grand fir (Abies grandis (Dougl.) Lindl.), western redcedar (Thuja plicata Donn.), western hemlock (Tsuga heterophylla (Raf.) Sarg.), red alder (Alnus rubra Bong.), tanoak (Lithocarpus densiflorus (Hook. & Arn.) Rehd.), madrone, and bigleaf maple (Acer macrophyllum Pursh);
- Lodgepole Pine (3%) - mostly lodgepole pine, but may include some red fir; and
- Jeffrey Pine (3%) - mostly Jeffrey pine with some ponderosa pine, Coulter pine, sugar pine, lodgepole pine, incense cedar, and red fir. Black cottonwood (Populus trichocarpa Torr. & Gray), aspen (Populus tremuloides Michx.), and California black oak are hardwood associates.

The five remaining noncommercial conifer vegetation types are Juniper (Juniperus spp. Carr.) (6%), Pinyon Pine (Pinus monophylla Torr. & Fre.)-Juniper (6%), Montane Hardwood Conifer (5%), Subalpine Conifer (1%), and Closed-Cone Pine Cypress (0.2%).

Timber Production

Approximately 18% (7.5 million ha) of California's land is commercial forestland (USDA, 1982; CDF, 1988). Of the forestland not reserved for parks or wilderness areas, 52% is administered by the Forest Service, 23% is owned by approximately 120 forest industry companies, and 21% is owned by 60 to 100,000 NIPF owners. Timber from all private land accounts for almost 59% of the total harvested, 31% comes from national forests, and 10% from other public lands (CDF, 1988).

Most of the timber harvesting and manufacturing facilities are concentrated in the northern half of the state. In addition, 45% of the total harvest from industrial and NIPF lands comes from the North Coast region (CDF, 1988). Nearly all of the timber harvested in California remains in the state for processing. Almost 61% of the total wood used in the state is currently imported.

Timber harvesting in California has decreased significantly from a peak of 29 million m^3/yr in 1955 (CDF, 1988). Given current social, demographic, and economic trends, without global climate change, the CALPLAN simulation model (Davis et al., 1986) projected an annual harvest of 15 million m^3/yr in the year 2020 to 2030. Some timber harvest forecasts project slightly higher levels by assuming increased cuts from NIPF lands and more intensive management practices (CDF, 1988).

Given continuation of present trends, the main deterrents to the future productivity of forest resources are the conversion of forestland to other uses, wildfire, forest pests, management practices, and climate change. Nearly 2.0 million ha of forest and rangeland cover types were lost to urbanization and development of agriculture from 1950 to 1980. Another 0.9 million ha are expected to be converted over the next 30 years (CDF, 1988).

Water

Water is the most important and controversial product derived from the state's forests (CDF, 1988). Current needs for water now exceed the available supply. Although 70% of annual precipitation falls on forests in the northern third of the state, most of it is consumed by agriculture and urban populations in the southern half (Dudek, Volume C; Lettenmaier, Volume A). Precipitation is greatest in the winter and is lowest in the summer, when water demands are at their peak. In order to help overcome water imbalances, California has developed an extensive water storage and distribution system (Lettenmaier, Volume A; Dudek, Volume C). In addition, water from Oregon and the Colorado River is imported to meet total water needs.

The driest year in California's recorded history was 1977. That year was also the second successive dry year of the worst drought of more than 100 years of record. Average stream and river runoff was only 47% and 22% of average in 1976 and 1977, respectively. This drought is believed to have directly or indirectly caused the death of 5 to 12 million trees (CDF, 1988).

Recreation

The state parks, National Forests, and National Parks in California draw more annual visitors than those of any other state (CDF, 1988). Recreational use of national forests in 1986 amounted to 55 million RVD's (one RVD represents 12 hours of participation in any recreational activity by any individual); National Parks measured 19.9 million, state parks 15.3 million, BLM lands about 8.7 million, and all other federal lands about 5.4 million (CDF, 1988). The San Bernardino National Forest, located near Los Angeles, has the highest recreational use of any national forest. Yosemite National Park is the third most visited National Park in the country. The USDA Forest Service forecasts that national forests in California will have the most rapid increase in forest and rangeland recreational use of any region into the next century (USDA, 1981).

Forage

Livestock production is an important renewable resource of California's forests, ranges, and desert lands. The quality and volume of forage produced in different vegetation cover types depends greatly on precipitation patterns, density of overstory vegetation, and species competition. Approximately 35% of the forage consumed by livestock in 1985 came from the hardwood and conifer cover types (CDF, 1988). Although forage from forests is not as abundant or nutritious for livestock as rangelands, it is important to the livestock industry because it provides forage in the summer when little is available from grasslands.

Over the next 30 years, amounts of forage consumed by cattle and sheep are projected to decline by about 7% and 10%, respectively (CDF, 1988). These predictions are based on expected losses of rangeland to agricultural and urban uses, reductions in the nutritional quality of natural forage due to curtailments in spraying and burning of rangelands, and prices for beef and lamb.

Wildlife

Conifer forests provide breeding habitat for 108 species of mammals, 148 species of birds, and 55 species of reptiles and amphibians (CDF, 1988). Hardwood forests provide important habitat for other bird and mammal species, such as turkeys and feral hogs, two introduced wildlife species. Fishing and deer hunting are the most popular wildlife-related uses of forests. Nearly 2.5 million fishing licenses and 315,000 deer tags were sold in 1984 and 1985 (CDF, 1988). Most hunting and fishing takes place on federal and state lands, but an increasing number of private landowners sell hunting rights to their forestlands.

Factors Affecting Forest Health and Productivity

Wildfire. On the average, wildfires have damaged more than 133,000 ha of forests and rangelands in California each year since 1980 (CDF, 1988). In southern California, a variety of critical fire periods combine to produce an essentially year-long fire season (Pyne, 1984). Fires tend to be large and episodic, often with urban-related causes. In northern California, there is a distinct summer fire season as a result of low precipitation during those months (Pyne, 1984). Almost 60% of the fires in the Pacific states from 1973 to 1978 were caused by lightning (USDA, 1980).

Insects and Diseases. The annual loss of merchantable timber to insects and diseases is thought to be substantial (CDF, 1988). Bolsinger (1980) estimated insect losses to be 23% of the total tree mortality in California's interior forests during the late 1960s and early 1970s.

The most harmful forest insects are bark-cambium feeders and defoliators such as the western pine beetle (Dendroctonus brevicomis LeConte), mountain pine beetle (Dendroctonus ponderosae Hopkins), Douglas-fir beetle (Dendroctonus pseudotsugae Hopkins), red turpentine beetle (Dendroctonus valens LeConte), fir engraver (Ips spp.), pine engraver (Ips spp.), flatheaded fir borer (Melanophila drummondi Kirby), and the California flatheaded borer (Melanophila californica Van Dyke) (CDF, 1988). The most important defoliators are the Douglas-fir tussock moth (Orgyia pseudotsugata McDunnough), budworms, needle miners, and the gypsy moth. Dwarf mistletoe (Phoradendron spp.) is the most common disease causing tree mortality, affecting as much as 15% to 25% of Douglas-fir and other pine and fir species (CDF, 1988). Major diseases include annosus root rot (Heterobasidion annosus (Fr.) Bref.), Armillaria root rot (Armillaria spp.), and black stain root diseases (Xylaria spp.). White pine blister rust (Cronartium ribicola Fischer) affects many species of pines.

Air Pollution. There is growing public concern about effects of air pollution on California's forests. Ozone is the only regionally dispersed pollutant which is presently known to occur in concentrations high enough to cause foliar injury to some sensitive trees (Woodman, 1986, 1987a). Los Angeles has the highest measured ozone concentrations of any city in the country. Miller (1983) and others have identified ozone symptoms in 12 conifer and hardwood species in southern California. Injured trees tend to have a greater susceptibility to droughts, reduced growth rates, and fatal attacks from bark beetles and root diseases than uninjured trees.

Trends in Forest Management

Most of the commercial forest types in California occur on relatively steep mountainous terrain which is not suitable for uses other than forestry (Tappeiner et al., 1986). The more accessible virgin forests in the coastal areas and lower Cascades and Sierras were logged in the late 1800's and early 1900's. Preferential harvesting of pines have resulted in Sierran forests dominated by shade-tolerant fir species. The interior forests, e.g., eastside ponderosa pine and lodgepole pine, have been repeatedly logged over many years as merchantable species and sizes changed. Most forests are now dominated by young-growth rather than old-growth stands.

Over the last 30 years, timber management practices have included salvage logging of dead and dying trees, intensive site preparation and tree planting, control of animal damage (e.g., porcupines, rodents), release of conifer seedlings from competing shrubs and hardwoods, and thinning (Barrett, 1980; Tappeiner et al., 1986). Relatively few trees are planted due to cost and poor survival. Ponderosa pine and Douglas-fir are the species most commonly planted.

California's "forest practice rules" are viewed as being more restrictive to management of private forestlands than similar regulations in other states (Tappeiner et al., 1986). These laws require that timber harvesting and regeneration plans for private lands be prepared by a licensed professional forester and approved by a state forest-practices official (Tappeiner et al., 1986). The species, stocking rates, and time within which reforestation must be accomplished are prescribed. In addition, some counties have ordinances which regulate stand densities after partial cutting and the silvicultural system to be employed in some forest types.

Tappeiner et al. (1986) and Woodman (1987b) forecast that most private forest owners will adopt a graduated system of forest management intensities over the next few decades. These zones of management intensity will be shaped by considerations such as forest site productivity, proximity to manufacturing facilities, harvesting costs, and availability and cost of transportation facilities. They will also consider topography, competition with other sources of timber, availability of labor, and local ordinances. The most capital-intensive practices will be limited to those zones capable of providing the greatest financial return to owners. In zones where esthetics, watershed management, and other uses are dominant, timber management will be minimal.

SOCIOECONOMIC TRENDS AFFECTING FORESTS

Ten percent of the population of the United States are California residents. The state's $500 billion annual output of goods and services constitutes 12% of the U.S. gross national product. In 1985, service employment was

55% of total employment, manufacturing was 17%, and agriculture and forestry only 3% (CDF, 1988). The state is dominated by urban dwellers, whose attitudes and values play a major role in determining policy on the state's forests. Three southern counties contain 47% of the people, with 12% of the total (3.3 million) living in the city of Los Angeles. Almost 20% of the population lives in the San Francisco Bay area.

These demographic and socioeconomic conditions have resulted in a population which is wealthier and more educated than average, willing to make investments in public service, and more concerned about environmental issues than citizens in many other states (CDF, 1988). They have stimulated formation of a number of public interest groups who are politically active and able to exert influence on public policies related to environmental quality and management of private and public forestlands. These trends are not likely to change and may intensify with greater public information on global climate change and other environmental issues.

The 1988 report of the Forest and Rangeland Resources Assessment and Policy Act Committee identified a number of socioeconomic trends which may influence the effects of climate change on California's forests and citizens (CDF, 1988). These include the following:

- increasing needs for water and outdoor recreation;
- increasing demands for lumber, plywood, paper, and other wood products;
- a decrease in the ability of the state's forest industry to compete with other regions and maintain its present share of the nation's wood products markets;
- a reduction in the number of wood processing facilities and experienced forest labor;
- increasing demands for livestock products without price increases;
- increasing costs of owning and managing forests without compensating increases in wood prices;
- more public pressure to manage public and private forestland for noneconomic values, e.g., water and recreation; and
- increased state and county government regulations which limit opportunities for adequate financial returns to forest owners and managers.

PROJECTED CLIMATE-CHANGE SCENARIOS

The three hypothetical scenarios of global climate change in California postulate statewide increases in average monthly temperatures and slight decreases or modest increases in precipitation depending on the location. On an annual average basis, the GISS model-based scenario estimated the greatest mean change in monthly temperature (4.7°C) and precipitation (7.0 mm). The OSU-based scenario postulated the smallest changes in temperature (2.3°C) and monthly precipitation (0.5 mm).

A representative example of changes in monthly temperature and precipitation is shown for California's North Coast climate division in Figure 3A and 3B. The very productive Douglas-fir and coastal redwood forest types are found in this division. The GISS scenario had the highest individual monthly changes in temperature (+8.4° in September) and precipitation (+68 mm in March). The OSU scenario projected the smallest maximum monthly temperature increase (1.2° in January) and the GFDL the greatest monthly decrease in precipitation (-28 mm in January).

Figure 3 also illustrates some of the seasonal differences between scenarios and how they might influence future forest productivity and composition. For example, forest regeneration and good seasonal growth is dependent on having moist soils and low water stress conditions in the spring (March-April) and early summer

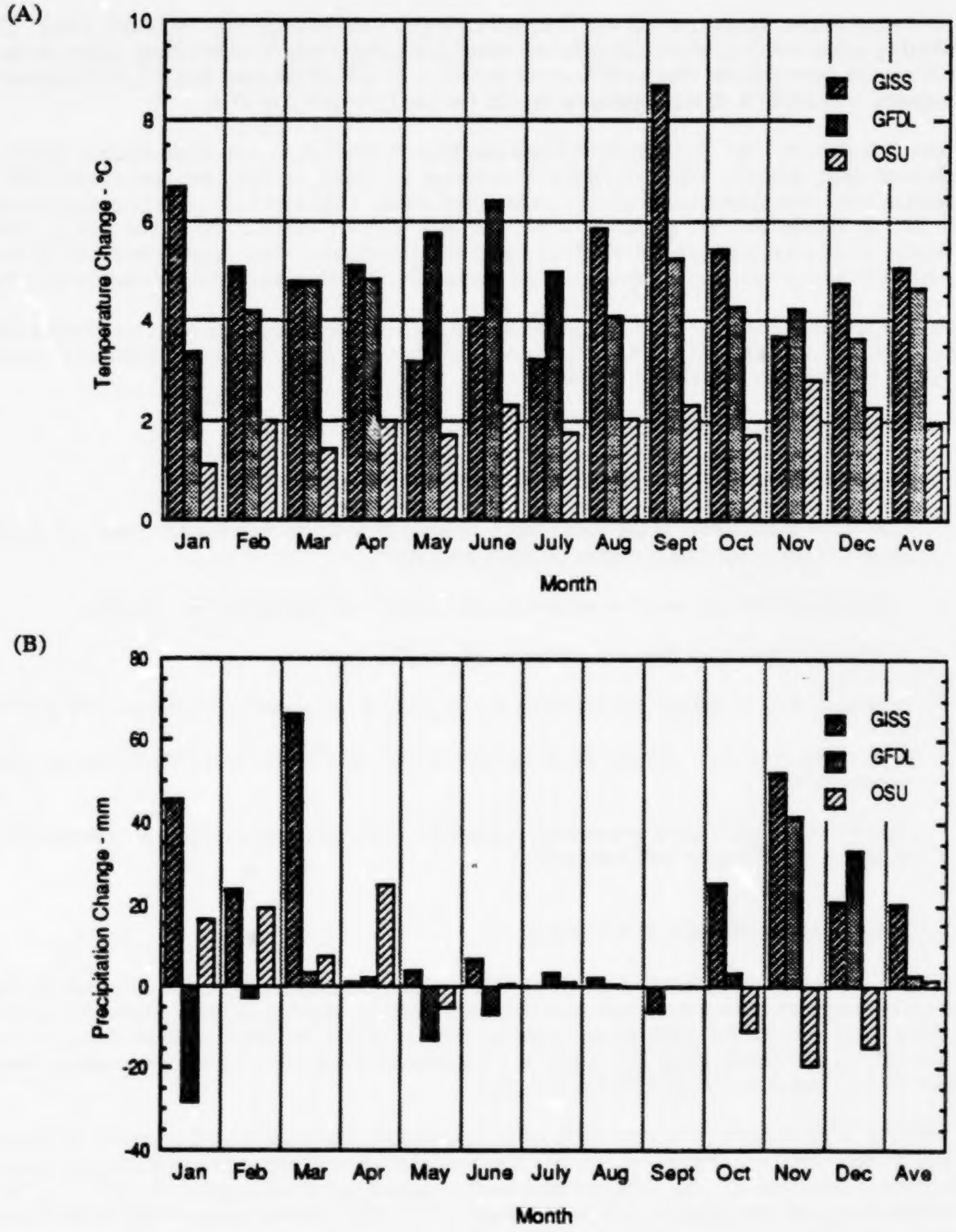

Figure 3. (A) Change in mean monthly temperature by scenario for North Coast Climate Division. (B) Change in mean monthly precipitation by scenario for North Coast Climate Division.

(May-June). High temperatures and water stress have a potentially greater impact on forests if they occur during these periods than they do after July. Thus, the conditions of the GISS scenario would have less negative impact on North Coast forests than the OSU or GFDL scenarios. GISS projections of higher winter and spring precipitation with warmer spring temperatures would provide the best growing conditions for these forests. Assuming that postulated higher spring rainfall cannot offset potentially drier soils due to less than average winter precipitation, the OSU scenario would have the greatest potential impact on forest survival and growth in this division.

Climate change scenarios for other state climate divisions generally postulate 10 to 60% less precipitation in May, June, and July. All climate scenarios for Southern California presume future growing season conditions which are 2.5° to 7.8° warmer and 5% to 50% less than the historic average. These conditions would primarily impact the noncommercial forest types in this part of the state. Climate change estimates for commercial forest types are similar to those depicted for the North Coast region.

POTENTIAL IMPACTS ON SPECIES COMPOSITION AND FOREST PRODUCTIVITY

Species Composition

No major assessment of the range of potential effects of global climate change on California's forest resources has been published. Davis (this volume) used fossil pollen samples to reconstruct the species composition of western Sierra Nevada forests growing at equilibrium conditions almost 9000 years ago when temperatures were 1°C higher and monthly precipitation 5 mm less than today. He concluded that much of the present forested area was sagebrush steppe and that pine and fir trees were less abundant than today.

Using a GFDL-based scenario, Leverenz and Lev (1987) concluded that the current natural range of Douglas-fir, western hemlock, and Englemann spruce (Picea englmannii Parry) in California would eventually disappear because of a reduced ability to naturally regenerate. They hypothesized that the conditions in this scenario would favor expansion of ponderosa and lodgepole pine. They assumed that up to a 50% increase in evaporative demand over available precipitation would be compensated for by benefits from higher CO_2 concentrations. If CO_2 cannot compensate to that extent, they postulated that the natural range of most western conifers would be diminished over an unspecified period of time.

Assuming that future climate change does not exceed the bounds of the three scenarios, there is no compelling scientific information to suggest that California will experience significant large-scale reductions in the distribution of major tree species within the next century. None of the projected climate changes appears severe enough to directly kill trees. Shifts in tree numbers and distribution will likely take place over hundreds of years through periodic extreme temperature or drought events and inabilities of some species to naturally regenerate themselves after catastrophic mortality from wildfires and insects and disease epidemics. Although some species may disappear from areas on the periphery of their natural ranges ("ecotones"), it seems unlikely that any of the hypothetical climate change scenarios would eliminate all individuals of a species from their present range.

The major commercial tree species most likely to be adversely impacted by climate change are those most sensitive to drought and high temperatures. These include Douglas-fir, western hemlock, red fir, and white fir. Most of the major pine species have evolved under warm and dry conditions and will likely not be greatly impacted. Changes in climate will probably have the greatest effect on trees occupying marginal habitats or peripheral areas of their natural ranges (Layser, 1980). These areas have undergone the greatest contraction and expansion during past cyclic periods of temperature and precipitation change.

Forest Productivity

Higher temperatures (and concomitant, increased evapotranspiration demand), combined with small or no increases in precipitation, will create drier summer conditions. The most probable short-term effects of such conditions on low-elevation forests will be decreased annual growth. Forests growing above 1,500 m elevation could become more productive as a result of warmer temperatures and longer growing seasons, although their natural ranges may be decreased. The thresholds between no changes, decreases, or increases in forest growth cannot be estimated from available information.

Lavender et al. (1986) raised concerns that Douglas-fir and other cool climate species may experience reductions in growth and vigor solely from their inability to meet minimum "chilling requirements" in a future warmer climate. Douglas-fir seedlings need temperatures which do not exceed 5°C for 13 weeks (Lavender et al., 1986). In their assessment of climate change impacts on western conifers, Leverenz and Lev (1987) assumed that these requirements would be met if average temperatures did not exceed 9°C for one month. The OSU scenario is the only scenario which would meet the Douglas-fir chilling requirements in the North Coast climate division where this species is primarily located.

Any increase in temperature will likely increase the potential for damage by diseases and destructive populations of insects. Droughts are frequently followed by epidemics of bark beetles (Furniss and Carolin, 1977). One of the most notable effects of the California drought of 1976 and 1977 was a significant increase in tree mortality as a result of bark beetle attacks (CDF, 1988). Increased temperatures and relatively drier conditions projected by all scenarios will increase the likelihood of wildfire occurrences and the danger posed by fires once they start.

Potential Impacts on Forest-Based Socioeconomic Systems

The most likely impact of climate change on current socioeconomic trends are 1) increased disincentives to private owners and industry to manage forests for timber production, 2) additional need for production of water from forests, 3) increased demands for forest-oriented outdoor recreation experiences, and 4) increased need to salvage trees killed or injured by wildfires, insects, and diseases.

The trends described in the Forest and Rangeland Resources Assessment and Policy Act report (CDF, 1988) raise the question of whether or not private and industrial forestlands will be able to yield acceptable financial returns to their owners by the time of CO_2 doubling. The increased risks likely to be associated with future forest management may result in further reductions in the size and value of industrial forests in the state. Profit margins have decreased significantly for most timber companies due to higher harvesting costs, higher labor costs, old and inefficient mills, and state and local restrictions on timber harvesting and forest management. Without substantial increases in the value of timber, or fees paid to forest owners for use of their forests for recreation and generation of water, the size and viability of the forest industry will undoubtedly decrease.

Climate change will not likely alter the present trend in management policy on national forests, national parks, or other federal lands. Assuming that effects of climate change are relatively subtle, the current trend in public demand for water and recreation will dominate policy considerations on these lands. The importance of water yield in national forest management plans is increasing and will continue to influence the use of national forests without climate change. If climate change reduces water yields, recreation and water supply fees could be established to help balance revenue reductions from timber sales. Future forest management practices will be dominated by needs to increase water from forested land, reduce risks of major insect epidemics, and salvage dead trees. Utilization of salvaged trees may require some level of price support in order to maintain and encourage local wood utilization capabilities and a skilled labor force.

CONCLUSIONS

Projected warmer temperatures and possible shifts in precipitation would most likely decrease productivity and species diversity in many low-elevation California forests. Higher-elevation forests could experience greater productivity and an increase in the number of species. Higher winter temperatures will reduce mountain snow packs and summer stream flows. Some of the potential negative effects of climate change could be ameliorated by beneficial effects of CO_2, and the large number of tree species which have developed varying tolerances to extremes of temperature and water stress. Annual tree mortality will likely increase due to more wildfires, greater insect populations, and increases in diseases.

The state's distinctive socioeconomic trends will most likely continue to greatly influence forest use and management, regardless of climate change. All forest managers will devote more attention to activities which increase water production, provide more forest recreation opportunities, and lower the risk of catastrophic losses to insects, diseases, and wildfires. Potential decreases in forest productivity and losses of forestland to other uses, will most likely intensify public pressure to legislate more multiple-use practices on private forestlands. Most timber harvesting from federal and state lands will come from tree salvage and forest sanitation operations which remove dead, dying, and susceptible trees.

CHAPTER 4

POTENTIAL CLIMATE CHANGE EFFECTS ON SOUTHEASTERN FORESTS

INTRODUCTION

The South, or Southeastern Region of the United States, includes the states of Virginia, North Carolina, South Carolina, Georgia, Florida, Tennessee, Alabama, Mississippi, Arkansas, Louisiana, Oklahoma, and Texas. It has been called the "nation's wood basket" because of its importance in the production of wood and the manufacture of wood products. Its mild climate, long growing season, and favorable precipitation provide conditions conducive to the production of timber and many agricultural crops. These states contain approximately 40% of the country's commercial forests, from which almost half of the nation's timber is harvested each year (USDA, 1982).

Geography and Climate

Compared to California, the topographic relief of the forested areas in the South is relatively flat (Britannica, 1982). The largest and most productive of three subregions is the Coastal Plain, encompassing 45% of the area (Figure 4). It is a low-lying and flat 250- to 650-km-wide strip along the coast. It contains the Mississippi River Delta, Coastal Flatwoods, and the Florida Peninsula. The Piedmont is the subregion between the Coastal Plain and Appalachian mountains. It has a mild topographic relief characterized by rolling hills and narrow streams at elevations of 100 to 250 m above sea level. The Uplands subregion incorporates high plateaus, steep ridges, and mountain peaks with elevations ranging from 300 m to 2000+ m. The Uplands include the Blue Ridge Mountains, the Appalachian Plateau, the Ouachita Uplands, and the Ozark Plateau.

The Southeast has a continental climate with maritime influences which is characterized by moderate to cool moist winters and moist warm summers (Britannica, 1982). The 1000 to 1500 mm of annual precipitation is generally well distributed over the year and droughts are more common in the spring and fall than in the summer. East Texas and Oklahoma have the lowest average precipitation (82 mm/month) and greatest frequency of severe spring droughts. Louisiana, Mississippi, Alabama, and Florida have the highest rates (110 to 118 mm /month). Monthly precipitation is highest between June and September in the Coastal Plain and January through August in the Piedmont and Uplands.

Mean annual air temperatures range between 164° to 20°C (Britannica, 1982). The coldest temperatures (3.4° to 6.0°) occur in January and hottest (25° to 28°) in July. The highest temperatures and humidities occur in the south coastal areas. Historically, the probability of clear sunny days are 60% to 80% in the summer and 40 to 60% in the winter. Frost-free periods of 215+ days in the Coastal Plain and Piedmont permit forests to grow longer than in any other major forest region (USDA, 1969).

FOREST RESOURCES

Major Forest Types

More than 100 commercial tree species grow in the South (Boyce et al., 1986). According to the USDA Forest Service (1982), the major forest cover types in order of total forest area are as follows: oak (Quercus spp.)-hickory (Carya spp.) (31%); loblolly pine (Pinus taeda L.)-shortleaf pine (P. echinata Mill.) (24%); oak-pine (16%); oak-gum (Nyssa spp.)-cypress (Cupressus spp.) (14%); longleaf pine (P. palustris Mill.)-slash pine (P. elliottii Engelm. var. elliottii) (9%); elm (Ulmus spp.)-ash (Fraxinus spp.)-cottonwood (Populus spp.) (2%); maple (Acer spp.)-beech-birch (Betula spp.), white (P. strobus L.)-red (P. resinosa Ait.)-jack pine (P. banksiana Lamb.), and spruce (Picea rubens Sarg.)-fir (Abies fraseri (Pursh) Poir.) (0.4%).

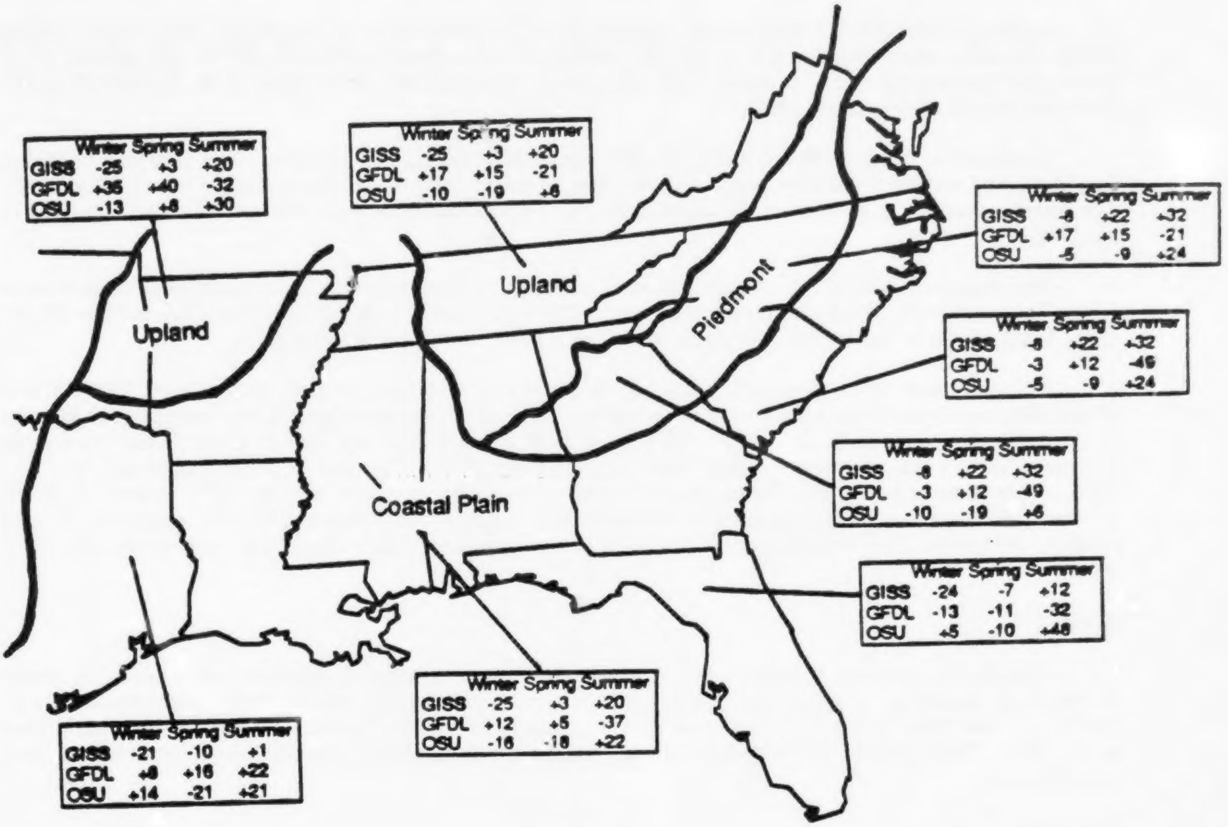
Winter Spring Summer
GISS -25 +3 +20
GFDL +35 +40 -32
OSU -13 +6 +30
Winter Spring Summer
GISS -25 +3 +20
GFDL +17 +15 -21
OSU -10 -19 +6
Upland
Upland
Piedmont
Winter Spring Summer
GISS -6 +22 +32
GFDL +17 +15 -21
OSU -5 -9 +24
Winter Spring Summer
GISS -6 +22 +32
GFDL -3 +12 -49
OSU -5 -9 +24
Winter Spring Summer
GISS -6 +22 +32
GFDL -3 +12 -49
OSU -10 -19 +6
Coastal Plain
Winter Spring Summer
GISS -24 -7 +12
GFDL -13 -11 -32
OSU +5 -10 +48
Winter Spring Summer
GISS -25 +3 +20
GFDL +12 +5 -37
OSU -16 -18 +22
Winter Spring Summer
GISS -21 -10 +1
GFDL +6 +16 +22
OSU +14 -21 +21

Figure 4. Percent change of seasonal precipitation projected by three climate-change scenarios for locations in three major physiographic regions of the South. Monthly values averaged for each season were: winter-November, December, and January; spring-February, March, and April; summer-June, July, and August.

Most of the pine types are found in the Coastal Plain and Piedmont (Boyce et al., 1986). The spruce-fir type is confined to ridge and mountain tops in the Appalachian Mountains. The oak-gum-cypress and elm-ash-cottonwood types are mostly found on moist sites near rivers and streams. The highest quality sites for hardwood species are in bottomlands. The oak-pine and oak-hickory cover types are especially important for production of wildlife and timber. Loblolly pine is the most commercially valuable tree species in the region (Boyce et al., 1986). Other commercially valuable conifer species are slash, longleaf, and shortleaf pines. The most valuable hardwoods are sweetgum (Liquidambar styraciflua L.), yellow poplar (Liriodendron tuplipifera L.), white oak (Quercus alba L.), southern red oak (Q. falcata Michx.), and northern red oak (Q. rubra L.).

Timber Production

Approximately 90% (76 million ha) of southern forests is classified as commercial timberland (USDA, 1982). In 1976, approximately 44% of the 283 million m^3 of softwoods and 50% of the 119 million m^3 of hardwoods harvested in the U.S. came from this region. Most of this timber came from Coastal Plain and Piedmont forests (Boyce et al., 1986).

Southeastern forest ownership differs greatly from California and other western states (Figure 2). Private individuals and nonforest industry companies own approximately 66% of the commercial forests (USDA, 1982). The forest indusry owns or leases 23%, and about 10% is in national forests or other public ownership (Alig et al., 1986).

Approximately 59% of the annual harvest of softwood species (primarily pine) come from nonindustrial private forests (NIPF), 32% from the forest industry, 5% from national forests, and 4% from other sources (Boyce et al., 1986). Most of the hardwood volume comes from NIPF and forest industry lands.

A large amount of the current forestland in the South was once used for agriculture (Healy, 1985). It was abandoned as marginal cropland after the 1930s and was allowed to naturally regenerate or was planted to forests in the 1950s through federal programs. NIPF land decreased 5% over the last 10 years; farmer ownership decreased 18%, while nonforest industry ownership increased 20%. The area of forestland owned by public agencies has remained constant. Forest industry acquired nearly half a million ha since 1977. Alig et al. (1986) estimated that forest industry acquisition of forestland may decline in the future and may be replaced with more intensive management on remaining lands and more long-term leases and cutting rights agreements with NIPF owners .

Water

Historically, abundant and well-distributed precipitation has adequately supplied public needs for water. Today, there is growing concern about the quality of future water supplies and how some forest practices, e.g., harvesting, road building, and use of herbicides, might contribute to river sedimentation and water pollution (Boyce et al., 1986). Public perception that forests are important sources of public water supplies is nominal compared to California.

Recreation

Although the economic importance of forest-based recreation in the South has not been fully assessed, it is an important part of the lifestyle of most people. More than 40% of the public is involved in nonconsumptive uses, e.g., wildlife observing, photography (Healy, 1985). More Southern adults hunt (29%) and fish (12%) than the national average. The Great Smoky Mountains National Park is the most visited national park in the country (CDF, 1988). Recreational demand in the South is expected to increase 50 to 60% over the next two decades (USDA, 1981).

Wildlife

Southern forests provide habitat for 170 species of amphibians, 720 species of birds, 204 species of mammals, and 209 species of reptiles (USDA, 1981). Forest land conversion and harvesting of old growth forests has decreased the area suitable for many species. Conversion of bottomland hardwoods to agriculture and mixed pine-hardwood forests to pine plantations are the most serious losses (Healy, 1985). Some endangered wildlife species, e.g., the red-cockaded woodpecker, which nests in old-growth pine forests, have been especially affected.

Factors Affecting Forest Health and Productivity

Wildfire. Although wildfires can occur during the entire year, most fires generally occur in the spring or fall after long periods of dry air (Pyne, 1984). The frequency, severity, and social attitudes about fires and forests are closely related to the cultural history of the South. Fires were deliberately set in frontier days, and today in some areas, for hunting, habitat and range improvement, and slash-and-burn subsistence farming. From 1973 to 1978, 55% of all fires were willfully set (incendiary) and 20% were caused by the burning of debris (USDA, 1980).

Due to improved fire suppression technology, annual wildfire damage has decreased from 12 million ha in the 1930s to 0.8 million in the 1980s (Simard and Main, 1987). Fire frequency influences the composition of forestland: frequent fires encourage shrub growth over pine; less frequent fire, pine over hardwoods; and infrequent fire, hardwoods over pine. Longleaf pine has been nearly completely replaced by loblolly and shortleaf, which is favored by less frequent fire (Pyne, 1984).

Insects and Diseases. The most economically destructive forest insect is the Southern pine bark beetle (Dendroctonus frontalis Zimmerman) (Kalkstein, 1981; Hedden, 1987). It attacks dense pole- or sawtimber-size pine trees which have usually been weakened by prolonged drought stress.

The most serious diseases affecting pines are the following: fusiform rust (Cronartium quercuum (Berk.) Miyabe ex Shirai f. sp. fusiforme Burdsall & Snow), brown spot needle blight (Scirrhia acicola (Dearnb.) Siggers), littleleaf disease (Phytophthora cinnamomi Rands), needle blights, pitch canker (Fusarium moniliforme Sheld. var. subglutinans Wollenw. & Reink.), and Annosus root rot (Heterobasidion annosus (Fr.) Bref.). Fusiform rust and brown spot blight damage and/or kill trees under 10 years old. Needle blight, pitch canker, and Annosus root rot generally weaken trees by injuring needles, branches, and reproductive structures. Warm, moist weather conditions favor the spread of all of these diseases.

The most serious insect and diseases impacting hardwood forests are hardwood borers (Styloxus spp.) and oak dieback or decline (Sphaeropsis quercina Cke. & Ell.). Hardwood borers attack and kill twigs and branches on oaks. Unfavorable weather conditions predispose red oak, chestnut oak, and other oak species to oak decline, which kills twigs, branches, and leaves of infected trees.

Soil Fertility. Soil fertility is a major factor in the productivity of southern forests (Allen and Morris, 1983). Most soils tend to be relatively old and well developed, to be highly acidic, and to contain relatively few weatherable minerals. They also tend to be low in calcium and magnesium, with most organic matter on the surface (Gregory, 1983). Nitrogen and phosphorus are the nutrients which limit growth on most Southern soils (Allen and Morris, 1983). Many Piedmont and Upland soils have been severely eroded.

Forest Productivity. One of the main reasons that the South is the most important timber region in the country is the high growth rates of southern pines. Unmanaged, naturally regenerated, well-stocked stands of loblolly, slash, and shortleaf pine on average soils produce 2000 to 2500 m^3/ha of wood in a 30-year rotation (time from regeneration to harvest) (Schumacher and Coile, 1960). Unmanaged and managed plantations grow 40 to 125% more wood than comparable natural stands (Coile and Schumacher, 1964; Clutter et al., 1983). Plantations established on "old fields" (abandoned farmland) produce 20 to 50% more wood than forested sites which were never farmed (Coile and Schumacher, 1964). High growth rates, short rotations, and low harvesting costs offer forest owners the highest financial returns on forest land of any region in the country.

The region's standing hardwood resource has been increasing in all subregions except the Mississippi Delta (Boyce et al., 1986). Annual net growth of hardwood forests is 2.2 times greater than the rate of harvest. Approximately two-thirds of the current total annual growth is in small trees less than 50 years old.

Boyce et al. (1986) stated that many private landowners who invest in pine plantations do so on the basis of hope for high financial rewards rather than on historical certainty. Based on the 1967 producer price index, the noninflated price paid for hardwood and pine pulpwood and sawtimber has declined or had no major appreciation since 1955 (Skog and Risbrudt, 1982). This was attributed to an oversupply of low-cost natural timber and advances in manufacturing technology which permitted utilization of smaller trees and wood waste from manufacturing processes.

Recent forecasts of shortages in future softwood supplies in parts of Virginia, North Carolina, and Georgia has been called the "pine regeneration" problem (Healy, 1985). It has been attributed mainly to inadequate pine reforestation on NIPF lands. In addition, although an increasing amount of land is being planted to pines, the total hectares in pine is declining (Knight, 1985). Many harvested pine forests are naturally succeeding to oak-pine and upland hardwood forest types because of inadequate regeneration. Other causes are the conversion of pine forestland to agriculture and other uses, higher than average mortality rates in natural pine forests, and an apparent slowdown in growth of some forests (Sheffield et al., 1985).

The determination of a growth slowdown was based on an analysis of sample trees in U.S. Forest Service inventory plots in five Southeast states (Sheffield et al., 1985). Some forests grew 15% to 25% less in radial growth over the last one or two decades than in previous periods. Most of these sample plots were in natural pine and hardwood forests on NIPF land. Plots in industrial and public forests did not show the same decreases. Although many possible causes were suggested, analyses on some of the data indicated that 70% of the decrease could be attributed to older trees, higher tree densities, and more droughts than in the past (Zahner and Myers, 1986; 1987). Another explanation was that the earliest growth rates used in the comparison were biased by a high percentage of abnormally faster growing trees in "old field" plantations.

Trends in Forest Management

Expectations of high financial returns have induced many industrial and public owners to practice some of the most intensive forest management of any region in the world (Boyce et al., 1986). Standard cultural practices include piling and/or burning logging debris after harvesting, controlling of sprouting hardwoods with cultivation or herbicides before planting, and planting pine seedlings which have genetically improved growth rates, disease resistance, and wood quality (Daniel et al., 1979; Boyce et al., 1986; Smith, 1986). Many 2- to 7-year plantations are "weeded" with herbicides or prescribed burned to reduce hardwood competition (Boyce et al., 1986). The current 9+ million ha of pine plantations is projected to double by the year 2030 (Alig et al., 1986). Low-cost natural regeneration methods are used when owners choose not to invest in plantations (Boyce et al., 1986). Although longer time is needed to produce merchantable size trees, natural regeneration and inexpensive prescribed burning provide a financially attractive alternative (Boyce et al., 1986; Smith, 1986).

Most hardwood forests are regenerated naturally because their slower growth rates and lower log values produce relatively small financial returns. Almost all important hardwood species can regenerate well from seed or sprouts. Management of high-value hardwood species, e.g., black walnut, white and red oak species, require a series of selective cuts which remove species of lower value (Smith, 1986).

All Southern states provide some funding and cooperative assistance to private forest owners in fire control, insect and disease control, forest management planning, and silvicultural research (Boyce et al., 1986). General land-use planning and regulation have been limited due to public concerns against unnecessary infringement of personal property rights (Healy, 1985). Only Mississippi and Virginia have laws which regulate reforestation of private land after timber harvesting. These statutes are less comprehensive and restrictive than the laws in California and other western states.

SOCIOECONOMIC TRENDS AFFECTING FORESTS

The 12 Southeastern states are home to just less than one-fourth of the total U.S. population (Healy, 1985). The region experienced more than a 40% increase in population from 1960 to 1980, accompanied by an approximate doubling of per capita real income (Alig et al., 1986). The population is expected to increase 31% between 1980 to 2000, with the greatest increase in Florida (79%) and lowest in Alabama (13%) (Healy, 1985).

The region has many social and economic distinctions. Healy (1985) cited the South's low wage structure and lack of unionization, low living costs, changing racial and social attitudes, and warm winter climate as reasons for its population and economic growth of the last few decades. The average personal income per capita is below the national average in all Southern states except Virginia, and a greater percentage of Southerners than average live below the national poverty level (U.S. Bureau of Census, 1986).

The South has historically had a very large rural population compared to the national average (Healy, 1985). Although this is still the case, the rural population has shifted dramatically from farmers to nonfarm residents. Agriculture employed only 3.2% of the labor force in 1986 (USDA, 1987). The urban population is distributed among many small cities or nonsuburban towns (with less than 500,000 people) and a few large cities, such as Atlanta, Miami, Tampa, and New Orleans. Urban densities are very low, with a much greater than average amount of land per urban resident.

Many Southerners are politically conservative, placing great importance on state and individual rights and protection of those rights from infringement. Compared to California, public interest groups concerned about forest environmental issues have not been successful in influencing many public policy issues. This trend will most likely reverse as environmental issues come increasingly to the forefront and education levels foster a more informed public.

The annual value of the forest resource in the South has been approximated at $63 billion (Marx et al., 1986). The estimated value of forests in the four leading states are as follows: Georgia ($8.6 billion), Arkansas ($8.3 billion), Florida ($7.4 billion), and Alabama ($6.5 billion). Historically, the area of forestland has been related to the economic health of agriculture (Healy, 1985). When actual or expected farm incomes were high, forestland was cut and used for crops. When farming became marginal or unprofitable, the land was abandoned and reverted to "old field" natural pine or pine-hardwood forests. The amount of land in forests decreased 1.8 million ha between 1977 to 1985 (Alig et al., 1986). One-third of this area was in bottomland hardwoods (Boyce et al., 1986).

Socioeconomic trends related to forestry over the next 50 years without climate change includes the following:

- increases in softwood prices (USDA, 1982);
- relatively small increases in the area of forestland owned by the forest industry (Alig et al., 1986);
- increased demands for lumber, plywood, paper, and other wood products (USDA, 1982);
- increased opportunities for the export of wood products from the South (USDA, 1982);
- increased hardwood biomass compared to softwood (Boyce et al., 1986);
- increases in public pressure to manage public and private forestland for multiple uses rather than only timber (Boyce et al., 1986);

- losses of total forestland to urbanization and agriculture (Alig et al., 1986); and
- increased need for state and local incentive programs to increase management of most valuable tree species on private lands (Healy, 1985).

PROJECTED CLIMATE CHANGE SCENARIOS

The three hypothetical climate change scenarios developed for the South included average monthly temperature increases of 2.0° to 7.7°C, depending on month and location. Monthly temperatures from the OSU-based scenario were 0.5° to 2.5° lower than the other scenarios. The GFDL scenario projected temperatures 0.4° to 1.0° higher than the GISS scenario over most of the Coastal Plain and Upland regions. The GISS scenario was 0.4° warmer than the GFDL in the Piedmont.

The GFDL climate scenario was the only one with an overall average decrease in monthly rainfall. The GISS scenario predicted average monthly increases of 2 mm, 12 mm, and 7 mm in the Coastal Plain, Piedmont, and Uplands regions, respectively. The OSU scenario projected average increases of 7 mm in the Coastal Plain, 6 mm in the Piedmont, and 1 mm in the Uplands. The drier GFDL scenario had reductions of 6 mm in the Coastal Plain, 13 mm in the Piedmont, and remained unchanged in the Uplands.

Monthly precipitation changes averaged over the year obscure the seasonal variability which is most important to the growth and survival of Southern forests. Estimates of percent changes in winter, spring, and summer precipitation for eight representative climate divisions are shown in Figure 4. In all locations, the GISS scenario had less than average monthly precipitation in winter and more than average in summer. Smaller increases in spring precipitation were postulated for all but two Gulf Coastal Plain sites. The GFDL scenario presumed much drier summers in all locations except east Texas. GFDL winter and spring rainfall were higher than the historical average except in Florida. In six divisions, the OSU scenario projected less than average precipitation in winter and spring, and more than average summer rain in all locations.

From a forest effects perspective, less than historic precipitation in winter and spring would probably have the greatest negative impacts on forest regeneration and seedling growth. Drier summers would most likely reduce forest growth and predispose trees to attacks from insects and root diseases. None of these scenarios was consistently worse or better than others. OSU's drier winters with drier springs make conditions harsher for forests in five of the eight locations. Wetter winters and wetter springs in the GFDL scenario would be the least harmful in five divisions. GISS results are the most variable among the sites, and potential impacts would depend on the specified conditions at each location.

POTENTIAL IMPACTS ON SPECIES COMPOSITION AND FOREST PRODUCTIVITY

Species Composition

Climate change will decrease or increase species diversity depending on the ecosystem, the genetic diversity of the species, the migration rates of new species, and many other factors (Layser, 1980). Using a relatively hot and dry climate scenario and results from a forest succession analysis by Solomon et al. (1984), Miller et al. (1987) concluded that the natural range of loblolly pine would move northward and increase in area by 16,000 ha. Although no time frame was emphasized, the process would require many centuries. The northern limits of loblolly are controlled by the frequency and severity of spring frosts (Fowells, 1965). The projected loss of area in East Texas, Oklahoma, Arkansas, and Coastal Plain was based on severe drought conditions projected by this scenario. None of the scenarios described above project conditions that are as severe. No compensating effects of higher CO_2 concentrations were considered.

Urban and Shugart (this volume) applied the GISS scenario to their mixed-species forest succession model in order to evaluate long-term climate change on an oak-pine forest type in eastern Tennessee. Assuming no effects from higher CO_2 or migration of new species into the ecosystem, they concluded that the warmer and drier conditions would lead to the elimination of chestnut oak, black oak, and pine species from the forest type. Using another climate change scenario, Field et al. (1988) evaluated potential long-term impacts on wetland ecosystems in the Tennessee River basin. They concluded that the warm-and-wetter scenario would eliminate less water-tolerant species due to a higher frequency of spring flooding.

One of the cover types most likely to be negatively affected by increased temperatures is the Fraser fir-red spruce type found above 1400 m elevation in the Southern Appalachian Mountains. Delcourt and Delcourt (1984) suggested that present climate warming has limited the re-expansion of this cover type since the late Holocene. Higher temperatures would most likely severely limit or eliminate the natural range of Fraser fir, red spruce, and other colder climate species in the southern mountains.

It is apparent that changes in forest species composition will be very region-specific. Changes in species will be influenced by the actual scenario of climate change which comes into play in a particular region, especially actual changes in precipitation, and local topographic and soil conditions.

Forest Productivity

Most existing forests will probably experience some decrease in productivity due to higher temperatures, if higher CO_2 concentrations and/or more moist conditions in the spring and summer do not compensate for higher respiration and evapotranspiration rates. The potential magnitude of losses cannot be estimated at this time. Existing growth and yield models are reliable only for forests grown in historical climate conditions. None of the forest succession simulation models were designed for growth and yield estimations (Solomon and West, 1987). Unmanaged older forests will be most vulnerable to decreased productivity.

Decreases in productivity and species diversity may be compensated for by planting tree species which are better suited to warmer climate, e.g., Caribbean pine, various Mexican pines, and several eucalyptus species. Kellison and Weir (1987) suggested that the genetic diversity of current species is large enough to select and propagate families and clones of trees which will grow well in a new climate.

Associated Effects

Sea Level Rise - A large area of southern forests grow on the Coastal Plain on soils that require drainage in order to be productive. Rises in sea level would impact an unknown portion of these forests through increased flooding, saltwater intrusion, and ineffectiveness of drainage systems. The areas of highest risk are the northeast North Carolina coast and the southern tip of Florida because of their low topography.

Wildfires - Increased temperatures, if not compensated for by increased precipitation, will undoubtedly increase losses of forests to wildfires. Assuming no change in the distribution of precipitation, Simard and Main (1987) estimated than an average temperature increase of 2.4°C and a 4% decrease in annual precipitation would increase wildfire occurrence in the South by 8%. All of the current GCM climate models project higher temperatures (Kellogg, 1987). As shown above, some locations in the region may become drier and others wetter. The OSU scenario, which projects dry springs, would severely increase fire danger.

Insects and Diseases. The potential effects of climate change on southern pests will depend on the magnitude of temperature increases and changes in moisture conditions. Higher temperatures will generally favor the northward expansion of the current range of most insects and diseases. Warmer temperatures will probably increase the population levels and range of southern pine beetles (Kalkstein, 1981), and Nantucket pine tip moth in some areas (Hedden, 1987). Drier conditions would favor decreases in severity of brown spot and rust diseases but increasd losses from littleleaf disease and annosus root rot. In general, forest pest problems will be greatest in stands that contain trees which are stressed or of low vigor (Hedden, 1987).

Potential Impacts On Socioeconomic Systems and Policies

Almost any climate change will heighten future public concerns about land use. Projected changes in the area and productivity of agricultural land in the United States and other areas in the world (Cooper, 1982) will provide a stimulus to convert the South's most productive forestland to agricultural production in areas where water supplies and soil conditions permit. Since much of the most productive land is now used for pine production, the loss of this land will contribute to further shortages in the long-term supply of softwood in the region. If this occurs, federal and state policymakers will need more comprehensive land-use planning, state and regional land use zoning, and new forest protection and incentive legislation.

Private forest owners will face increasing pressure to use their land for agriculture or to establish and manage pine plantations to meet expected shortages in softwood. If production of food or wood declines in other areas, prices and the potential profitability of land ownership will undoubtedly increase in the South. The needs of NIPF owners for short-term profits will likely influence them to sell or use their land for food crops. Nonforest industry owners, who have purchased forestland for investment purposes, will likewise choose the alternative which gives them the highest economic return.

Climate change will not likely impact the southern forest industry as quickly as other private owners because of long-term strategic planning, intensive management practices, and shorter rotations between regeneration and harvesting (Malac, 1987). Industry managers will most likely sell land with the lowest potential financial returns and intensify management on their best land. Those paper and solid wood products companies which depend on large supplies of softwood for their business will probably buy more land and intensify management practices on their existing land in order to ensure their future profits.

Given the additional losses of pine forests because of climate change, future softwood supplies are not likely to meet demands in many areas of the South. Many companies will be forced to use available hardwood resources, move their manufacturing facilities to locations with favorable softwood supplies, or cease operations. Companies which are very dependent on wood from NIPF and public forests will be most vulnerable to decreased wood supplies and increased prices. These and other companies with timberland may decide to move out of the South when their mills become technologically inefficient and greater profits can be made by investing in new facilities or land in other forest regions.

Cubbage et al. (1987) outlined the possible economic impacts of global climate change on commercial forests and forest-based industries. Using a 10% decrease in loblolly pine volume production, they estimated a $98 million per year loss in average cost of standing timber sold to a buyer. Further economic losses could occur from decreased quality of pulpwood (because of lower specific gravity of wood produced), shifts in forest management practices, and relocation of pulp and saw mills to more economically favorable locations in other regions. Southern forestry economic models assume that all direct-value-generated contributions of forest products have an indirect multiplier effect of 2.3 on other economic sectors (Cubbage et al., 1987). Thus, effects on the forest industry would have significant impacts on other aspects of southern economic life.

Given the size, location, and policies controlling management of public forestlands, public forests would be impacted in the same ways as described for public ownership in California. Climate change and current federal agency policies will emphasize more long-range planning, multiple-use management, and less emphasis on timber production. A shrinkage in private forestland will increase recreational uses, watershed protection, and wildlife management activities in public forests.

The current downward trend in forest-based employment opportunities will also be accelerated by climate change. Projected decreases in the area of commercial forests, reduction in the number of manufacturing facilities, and more automated mills will reduce future labor requirements.

Climate change will increase the need for highly trained foresters and forest managers. Increased complexity and difficulty in meeting forestland owner needs will require greater knowledge about forest biology, new forest management regimes, and a greater environmental consciousness in the future.

Climate change will likely accelerate concern about most of the environmental issues described for California. These concerns include the adequacy of future water supplies, recreation, and wildlife habitat. Water quality and quantity will become a major concern as ground and surface water supplies become used more in irrigated farming. As the public becomes better informed about environmental issues, including the value of forests in ameliorating potential climate change impacts and reducing atmospheric CO_2 concentrations, policymakers will face more pressure to regulate practices on all forestland.

CONCLUSIONS

Higher temperatures, with or without increased precipitation, will most likely decrease the productivity of most Southeastern forests. Some Uplands forests which are now limited by low temperatures and short growing seasons would become more productive. The timing and relative magnitude of changes in forest productivity cannot be estimated at this time. Depending on the forest type and actual changes in climate, most impacts on forests will probably be gradual and occur over several centuries. Given present knowledge on species and trends in forest productivity, climate change will tend to improve hardwood productivity but decrease softwood production. Current trends toward converting the more productive pine land to agriculture will be accelerated, which would further decrease softwood supplies in the region. Forest industries dependent on large supplies of low-cost softwood will face increasing economic pressures to modernize their manufacturing facilities, increase the supply of softwood from their lands, purchase more land, or move to other regions with more favorable wood supplies. Potentially major losses of forestland to agriculture and urbanization would likely cause major price increases for timber, more comprehensive land-use planning and zoning, and greater regulation of forest practices on all private and public lands.

CHAPTER 5

POTENTIAL POLICY CONCERNS

KEY ASSUMPTIONS

The scientific basis for climate change rests on measured increases in greenhouse gases, projected emissions of these gases now and in the future, conceptual understanding of the global carbon cycle, and estimates from first-generation global circulation models (NAS, 1983). Although most knowledgeable scientists agree that global temperatures will rise regardless of actions taken now to control future emissions of these gases, significant uncertainties exist in all aspects of the issue. Likewise, even if climate does change according to one of the climate scenarios, there is considerable uncertainty about the potential impacts on the biology of forest ecosystems and socioeconomic trends in the United States and world.

From the perspective of potential effects on forest ecosystems and the benefits or values which the American people receive from forests, the most pressing immediate questions about climate change are: when? where? how much? and what can we do about it? The answers to these critical questions cannot be provided now with any degree of certainty or acceptable risk. We will need new information on the relationship between forest ecosystems and climate and weather systems, new and different forest management systems designed to reduce climate change impacts on the most important forest resources in a region, and development of regional, national and international socioeconomic models that can simulate or project how various scenarios of climate change might impact the goods and services derived from forests.

A major premise of this review is that public policy implications of global climate change on U.S. forests cannot be determined without assessing the potential effects on a region-by-region basis. Each climate-change scenario varies by region, so that the relative effect is region-dependent. The forests in each region contain different tree species, different soil and physiographic conditions, differing intensities of forest management, and current limitations of climate which will greatly influence their short- and long-term response to climate change. Potential changes in economic benefits from forests will also vary greatly between regions because of differences in forest ownership, the contribution of forest-derived values to regional economies, and opportunities for using forested land for agriculture.

A second major premise is that climate change impacts on a region's socioeconomic system will be a more dominant factor in determining needs for forest policy changes than direct effects on species diversity or forest productivity. A key factor in determining regional socioeconomic impacts is related to forest ownership. The amount of forestland in private or public ownership will influence both the nature of impacts and the manner in which public policy may alter these impacts. Federal forestlands already have a legislated policy which can rapidly respond to socioeconomic needs on a regional basis. Private forest owners are most likely to respond in proportion to impacts on the profits they derive from their forests. State and local government policymakers are most likely to legislate new policy or regulations concerning forest effects when forest-based tax revenues and socially important values derived from forests need protection.

POLICY ISSUES

The California and Southeast assessments suggest how different forest ownership patterns, historic uses of forests, and population demographics might interact with climate change to influence future public policy in those regions. Some limited extrapolations of these trends will apply to other forest regions:

- Public forestland managers will be more sensitive to public concerns and impacts on "noneconomic" values than private owners. Private owners will be more responsive to changes in financial effects, availability of low-interest capital, and the risks associated with long-term capital investments in forests, which will increase in an unstable and less favorable climate.

- Federal, state, and local policy makers will respond to impacts of climate change in proportion to the expressed concerns of citizen's groups, forest industry, and local governments. In states like California, where forests contribute relatively little direct economic value to the state's economy, shortages in nonvalued forest resources, e.g., recreation and water, will be more important factors in determining public policy than losses in timber supplies, forestry employment, or taxes.

- Potential impacts on future wood supplies and related socioeconomic values will most likely determine public policy in regions where forest-based resources are more important to the regional and state economies.

One of the greatest uncertainties affecting future public policy will be the need for converting suitable forestland into land for agricultural production. This need will intensify as climate changes. Policymakers will have to consider new or different land-use policies to encourage and protect forest management on private forestlands that are not suitable for agriculture. This will require intensive planning and zoning of lands for these purposes.

Another major factor which will influence future public policy is the dependence of the forest industry on NIPF timber. Inadequate regeneration and lack of intensive management on these lands has already resulted in projections of shortages in softwood in small areas in the South, Northeast, and Lakes States regions. If this trend is not reversed, the consequences of this problem on the industry and economies in those areas will be exacerbated further by climate change. This suggests that new incentive programs and forest protection laws must be considered to promote better regeneration practices and protection of private forests.

Other potentially important public policy questions are related to climate change:

- To what extent should the federal government help protect private forestland owners from catastrophic losses due to climate change?

- To what extent should the public underwrite credit for long-term investments on private forestlands given the nature of higher risks and uncertainties of forests achieving merchantable sizes in an acceptable length of time?

- Who will pay for the costly long-term research needed to answer critical policy questions and provide new technologies to ameliorate impacts on socioeconomic systems?

RESEARCH NEEDS

One of the highest priority research needs is for reliable and precise estimates of future climate change on a regional or local basis. Predictions should include expected frequency and severity of departure from mean monthly values, estimates of potential daily evapotranspiration, daily solar radiation, potential risk of freezing temperatures in early spring and fall, and the number of high temperature days in mid-winter.

Of equal importance is an improved understanding of how major forest ecosystems will respond to concurrent increases in atmospheric CO_2, higher temperatures, and changes in seasonal distribution of precipitation. Most of the research applicable to these issues has involved small plants over short time periods. Research is needed to be able to scale up from single plants to forest stands and ecosystems. It is essential that we be able to distinguish between effects on forest productivity that are related to climate change and those effects caused by variability in plant competition, different tree stocking levels, and normal environmental stresses.

Another very important research need is to determine the extent to which potential growth reductions and impacts on species diversity due to climate change might be compensated for by enhanced levels of CO_2. Such studies will require long-term experiments with plants growing under continuous high CO_2 exposures, along with increased temperatures and different water regimes. Information of differential effects on forest tree species, especially hardwoods vs. conifers, is vital to the prediction of species composition of natural forest ecosystems and potential effects on the forest industry.

CONCLUSIONS

This review and assessment can only identify some of the emerging issues, trends, and questions about the potential effects of global climate change on American forests. The need for more in-depth analyses and information from new research is obvious. Undoubtedly, the extent to which public policy makers fund new research, pass new laws, and deal with forest-related issues will be determined by its importance within the context of other problems related to climate change. Legislators will be faced with major funding needs related to effects of sea level rise on coastal cities, needs for irrigation development to offset decreased crop productivity, more nonpolluting electric power generation facilities, etc. Although the overall effects of climate change on forest ecosystems and associated goods and values may not be fully realized for a number of decades, we must begin now to improve our present understanding of the biological and socioeconomic factors that will determine those effects and allow the assessment of their importance in relation to other public policy issues.

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